FAIRCHILD HILLER
SPACE AND ELECTRONICS SYSTEMS DIVISION

FABRICATION FEASIBILITY STUDY OF A 30 WATT/POUND ROLL-UP SOLAR ARRAY

FINAL REPORT

REPORT NO. 652-00101-FR
AUGUST 15,1968

PREPARED FOR THE

JET PROPULSION LABORATORY OF THE CALIFORNIA INSTITUTE OF TECHNOLOGY

UNDER CONTRACT NO. 951969

BY

FAIRCHILD HILLER CORPORATION
SPACE & ELECTRONICS SYSTEMS DIVISION
GERMANTOWN, MARYLAND

FAIRCHILD HILLER
CORPORATION

DATE August 15, 1968

SPACE AND ELECTRONICS SYSTEMS DIVISION

DOCUMENT NO.

652-00101-FR

TITLE

Final Report-Fabrication Feasibility Study of a 30 Watt/ Pound Roll-Up Solar Array

Contract No. 951969

No. Pages 100

PREPARED W. G. King
ORIGINATOR W. G. King

APPROVED
QA/REL/MAINT

APPROVED
MANUFACTURING

APPROVED L. Schreiber 9-1
SPEC AND STDS L. Schreiber

APPROVED J. Fernandez
ENGINEERING J. Fernandez

APPROVED W. King
PROGRAM W. King

APPROVED

APPROVED

REVISIONS

"This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, as sponsored by the National Aeronautics and Space Administration under Contract NAS7-100."

SESD 0013 8-67

ABSTRACT

The results of a study to determine the feasibility of fabricating a 250 square foot roll-up solar array capable of producing 30 watts/lb. or more of electric power are summarized. Three candidate structural systems having array deployment and retraction capability were evaluated in depth through parametric investigation of the various subsystems with weight minimization as the prime criteria. The study culminated in selection of an array panel deployment/ structural support system consisting of a folding beam using programmed joint motion. A preliminary design of the selected concept is presented with results of a deployment/retraction test program conducted on a full scale mechanically functioning model.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT.)

LIST OF TABLES

GLOSSARY

TEE	Tubular Extendable Element - Fairchild Hiller Trade-name for an unfurling, thin metallic ribbon, storable on a reel, which upon extension forms an open section tube of overlapped edges.
Hingelock TEE	Tubular Extendable Element - Fairchild Hiller Trade-name for an unfurling, thin metallic tube composed of two identical halves interlocked mechanically at their intersection and capable of being flattened and stored on a reel. The extended element has torsion capability far exceeding that of TEE elements.
Solar Cell Gross Area	That area enclosed by all solar cells, cell interconnect wiring, and cell and cell string spacing but not the peripheral area of physically separable modules, which is reserved for mechanical interconnection of modules or power collection harnesses.
Ploy Length	The distance required for an unfurling element to transition from a flat strip to its tubular shape.

1.0 INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

This document is the final report of a 1 year study contract to evaluate the feasibility of fabricating a 30 watt per lb. or greater roll up solar array. The work was conducted by Fairchild Hiller Corporation, Space and Electronics Systems Division, for the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. 951969. This report summarizes the activities conducted during the 1 year study, describes the flight hardware design and the functional model design which was generated to prove the feasibility of operation of the selected deployment/ retraction system, and present the results of the functional tests conducted on the model. Particular attention is paid to those activities conducted during the quarter of the program which have not been reported previously in the Quarterly Reports.

1.2 SUMMARY

During the last quarter of the program, beginning with the month of April and extending through June, activity concentrated upon fabrication of the full scale deployment model, the associated ground support equipment required for the deployment retraction tests, and accomplishment of these tests. Problem areas associated with a design of this type and the solutions of such problems which are incorporated in the model are identified. Possible solutions for problems which have not been solved are discussed. Tests results are presented which prove the feasibility of the folding arm design approach as an array panel deployment/retraction mechanism.

This report also summarizes the supporting analyses conducted by the various discipline areas, ie. design, electrical, thermal, materials sciences, reliability, and structural analysis. Additionally, the growth capabilities of the design are assessed.

Tables 1.2-1 and 1.2-2 present a design summary and an evaluation of array performance.

TABLE 1.2-1

DESIGN SUMMARY

	REQUIRED	DESIGN	
1.	30 Watts/Pound min.	34.49 Watts/Pound	(33.2)
2.	10 Watts/sq. ft. Nominal	10.39 Watts/sq. ft.	(10.00)
	A) 2 cm x 2 cm Cell .008 in. thick	2 cm x 2 cm Cell, .008 in. thick	
	B) 225 Cells/sq. ft. maximum	223.2 Cells/sq. ft	
	C) 49.5 mw/Cell Maximum at 140 mw/cm^2 55°C	49.5 mw/Cell @140 mw/cm^2 and 55°C	
3.	250 sq. ft. Nominal Panel Area	277.4 sq. ft. Nominal Panel Area	
4.	2.5 KW of Electrical Power Per Panel	2.76 KW Electric Power Per Panel	

TABLE 1.2-2

ARRAY PERFORMANCE EVALUATION

PARAMETER	REQUIREMENT	OBTAINED
Watts/Lb.	30	34.5
Cell Area	250 ft.^{2} nominal	277 ft.^{2}
Watts/Ft.^{2}	10.00	10.39
Mechanical Operation	Extend, Retract	Yes
NATURAL FREQUENCY	.04 Hz Minimum	
Beam Bending		.26 Hz
Beam Torsion		.36 Hz
Array Panel (5# Tension)		.078 Hz
ARRAY DEFLECTION	± 10° Solar Flux	
Thermal		1.3 in./36 ft.
Panel Tension		1.9 in./36 ft.
LAUNCH PACKAGING VOL. (FT.^{3})	566.7 (Available)	22.4
STRUCTURAL INTEGRITY	REQUIRED	M.S. = + (ALL)
ENVIRONMENTAL RESISTANCE	REQUIRED	SATISFACTORY
RELIABILITY	HIGH	.9998

2.0 TECHNICAL DESCRIPTION

This section describes the structural, mechanical, and electrical design selected as an optimum configuration of a roll-up solar array capable of producing 30 watts/lb. or greater of electric power. It summarizes the parametric studies and tests which were conducted to generate data upon which the design selection is based. Also contained herein is a description of a full scale model of the selected design which was fabricated and tested to demonstrate the capability of the design to deploy and retract. The results of the tests are presented and discussed and the design is evaluated as to its capability of meeting the design requirements as specified in JPL Specification 501407A, dated 1/4/67.

2.1 STUDY OBJECTIVES AND APPROACH

2.1.1 Design Requirements

The detail design requirements are defined in JPL Specification 501407A (Reference 1). The general requirements for the array and the study may be summarized thus:

Determine the feasibility of fabricating a roll-up solar array set which:

- Delivers 30 watts/lb. or greater at 1AU, AMO.
- Consists of 4 subarrays, each of 250 square ft. minimum solar cell gross area.
- Uses 1968 state-of-the-art technology.
- Exhibits deployment and retraction capability.
- Meets the environmental requirements of JPL Spec. 501407A.

Guidelines established for the study included:

- 2 x 2 cm x.008 thick N/P silicon solar cells shall be used which will produce a maximum of 49.5 mw of power at 55°C, 1AU, AMO. Furthermore, the design shall produce at least 10 watts/sq. ft. of gross cell area under the above conditions.

- Coverglass shall be .003 inch thick.
- The available packaging volume is defined in Ref. 1 and the array mounting surface shall be the periphery only of a 20" high x 100" wide plane. (Figure 2.1.1-1)
- The simulated missions shall include a Mars fly-by and a Venus fly-by with the array continuously exposed to the sun from the moment of first deployment.
- The study shall concentrate on the mechanical aspects of deployment/retraction, and survival under the environments specified in Ref. 1 (including ground handling, launch, boost flight, and space flight). Solar cell investigations shall be limited to those necessary for accomplishment of the above; however, magnetic fields shall be minimized and a reasonable design selected consistent with 1968 state-of-the-art of power conditioning and handling equipment.

2.1.2 Study Approach

Fairchild Hiller's approach to the study program was one of logical investigation without pre-judgement of the possible configurations. Accordingly, the following steps were taken in the conduction of the study:

- Identify Candidate Solar Array Configurations
- Conduct Parametric Studies
- Identify Dominant Factors Affecting Power/Weight
- Perform Fabrication Feasibility Study
- Select Base Line Configuration
- Optimize Base Line Design

- Generate Preliminary Flight Hardware Design
- Demonstrate Deployment/Retraction Capability In A Full Scale Model

The results of this study are presented in detail in Refs. 2, 3, 4, 5 and in this document which also summarizes the results of the cited references.

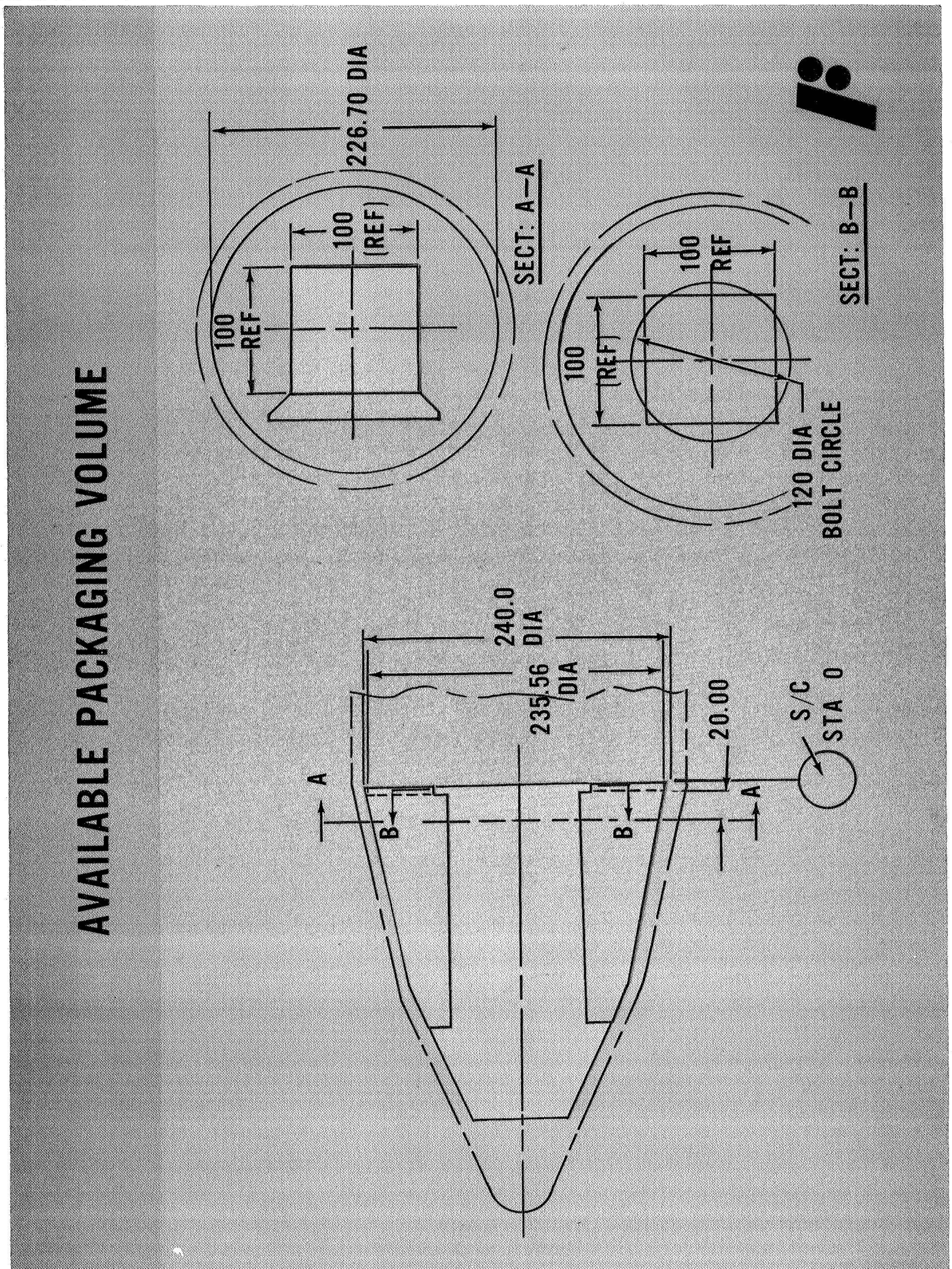

AVAILABLE PACKAGING VOLUME
226.70 DIA
100 (REF)
100 REF
SECT: A—A
100 REF
100 (REF)
120 DIA BOLT CIRCLE
SECT: B—B
240.0 DIA
235.56 DIA
20.00
S/C STA 0
A
A
B
B

Figure 2.1.1-1

2.2 BASE LINE DESIGN SELECTION

Various configurations have been proposed to support a flexible substrate, roll-up solar array. These fall into three basic groups, namely:

- Folding, rigid structures; usually a beam with programmed joint motion.
- Unfurling structural elements; this group is characterized by thin metallic elements, capable of being stored on a reel or in a cassette, which contain stored internal energy in their stowed configuration. Upon release or extension, the elements assume a tubular shape. The tubes may be closed or open sections.
- Inflatable and rigidized structural members.

Inflatable structures of light weight which are subjected to long periods of time in a space environment, usually are rigidized by some means such as a hardening foam so that structural integrity is maintained after loss of the inflating medium due to leakage or puncture by micrometeoroids.

The rigidizing process precludes subsequent retraction. For this reason, the inflatable system is considered not feasible for the intended application.

Folding, rigid structures usually employ a means of programming the joint motions to obtain the desired kinematic action of the assembly. Examples of these systems are the pantagraph, the scissors or "lazy-tongs" linkage, and the cable and pulley systems used in some drafting machines. These systems have been used with excellent and reliable results on many space vehicle programs including "Pegasus" and "Surveyor". This group was considered a prime candidate for the roll-up array structure, especially since the feasibility in this application area was proven on the Deployable Solar Array program conducted by Fairchild Hiller for Goddard Space Flight Center (Contract Number NAS5-9658), in which a model of a roll-up solar array for deployment on a spinning spacecraft was fabricated and successfully tested.

The unfurling structural element has received much impetus in the past 3 years through its development and application on satellites as antennae and gravity gradient booms. Several configurations are shown in Figure 2.2.1-1.

The Bi-Stem device has two attractive features: relatively short "ploy length" and simplicity of operation. However, several factors make it suspect for the intended application:

- The two tapes are stored on the same reel and induce relative motion between the tapes during deployment and retraction. This condition may lead to galling or seizing during operation in a vacuum.
- Meteorite penetrations in the region of overlapping may cause a weld to form which can prevent separation during subsequent attempts to retract. (This characteristic is common to all overlapping types of unfurling elements).
- The Bi-Stem is an open section element and hence has poor column load bearing capabilities in comparison with closed-section tubes.

For these reasons the Bi-Stem element was deleted from further consideration.

The welded tube, as depicted, is the subject of a concurrent study and is not considered in this study.

Fairchild Hiller manufactures "TEE" devices and has flown such on the Radio Astronomy Explorer satellite with complete success. The "Hingelock" tube is presently under development but is not considered developed to a state-

UNFURLING STRUCTURAL ELEMENTS

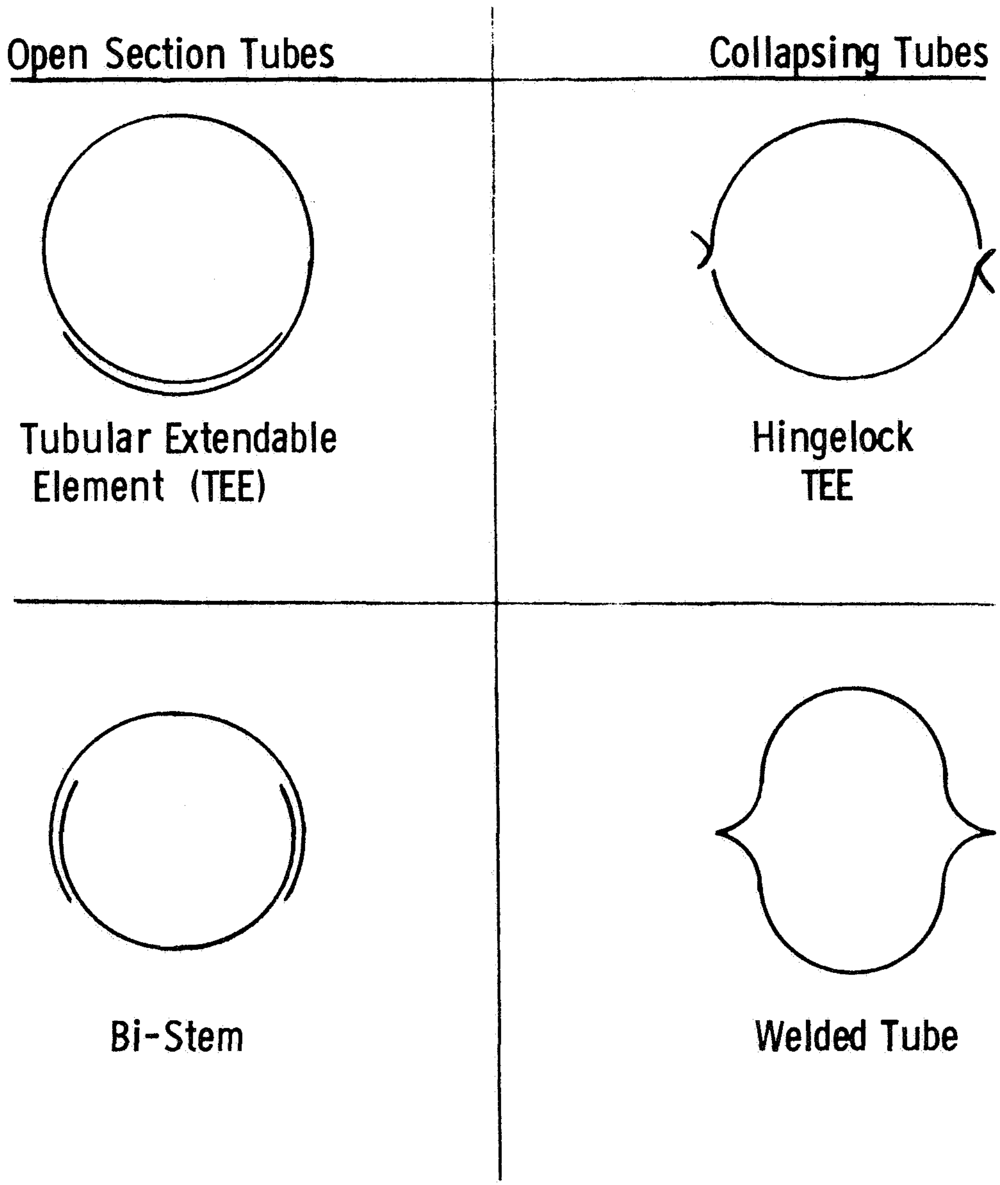


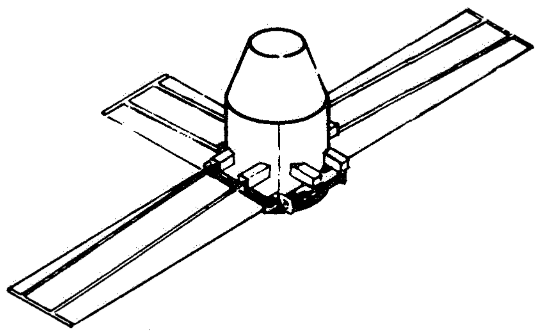
Figure 2.2.1-1

of-the-art at this time. Both systems were investigated in depth along with the folding arm concept in this study; however, preliminary studies (Ref. 2 and 3) indicated that the folding arm concept would best meet the requirements of the program.

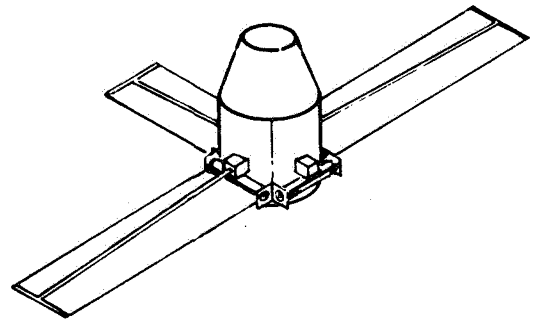
The folding arm system, for similar performance requirements, weighs at least 10 lbs. less than the dual TEE approach, and the Hingelock, while somewhat lighter than the folding arm, is not 1968 state-of-the-art. Accordingly, the folding arm system was selected for optimization studies and as the base line configuration. Figure 2.2.1-2 depicts the three configurations that were studied in depth to confirm the preliminary calculations and design selection.

Figure 2.2.1-3 illustrates the final configuration of the folding arm beam; Figure 2.2.1-4 pictures the Hingelock TEE.

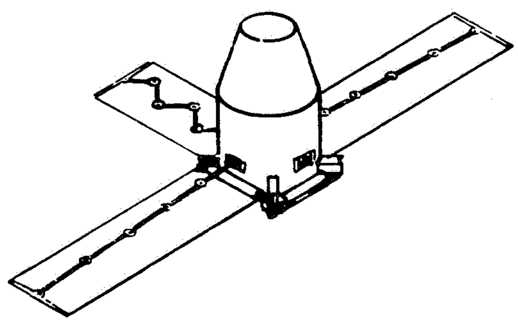
PANEL SUPPORTING SYSTEM CONCEPTS



ROLL-UP ARRAY TUBULAR
ELEMENT DESIGN



HINGE-LOCK ROLL-UP ARRAY
TUBING ELEMENT DESIGN



ROLL-UP ARRAY DEPLOYMENT
ARM DESIGN

Figure 2.2.1-1

ARRAY FOLDING ARM SYSTEM

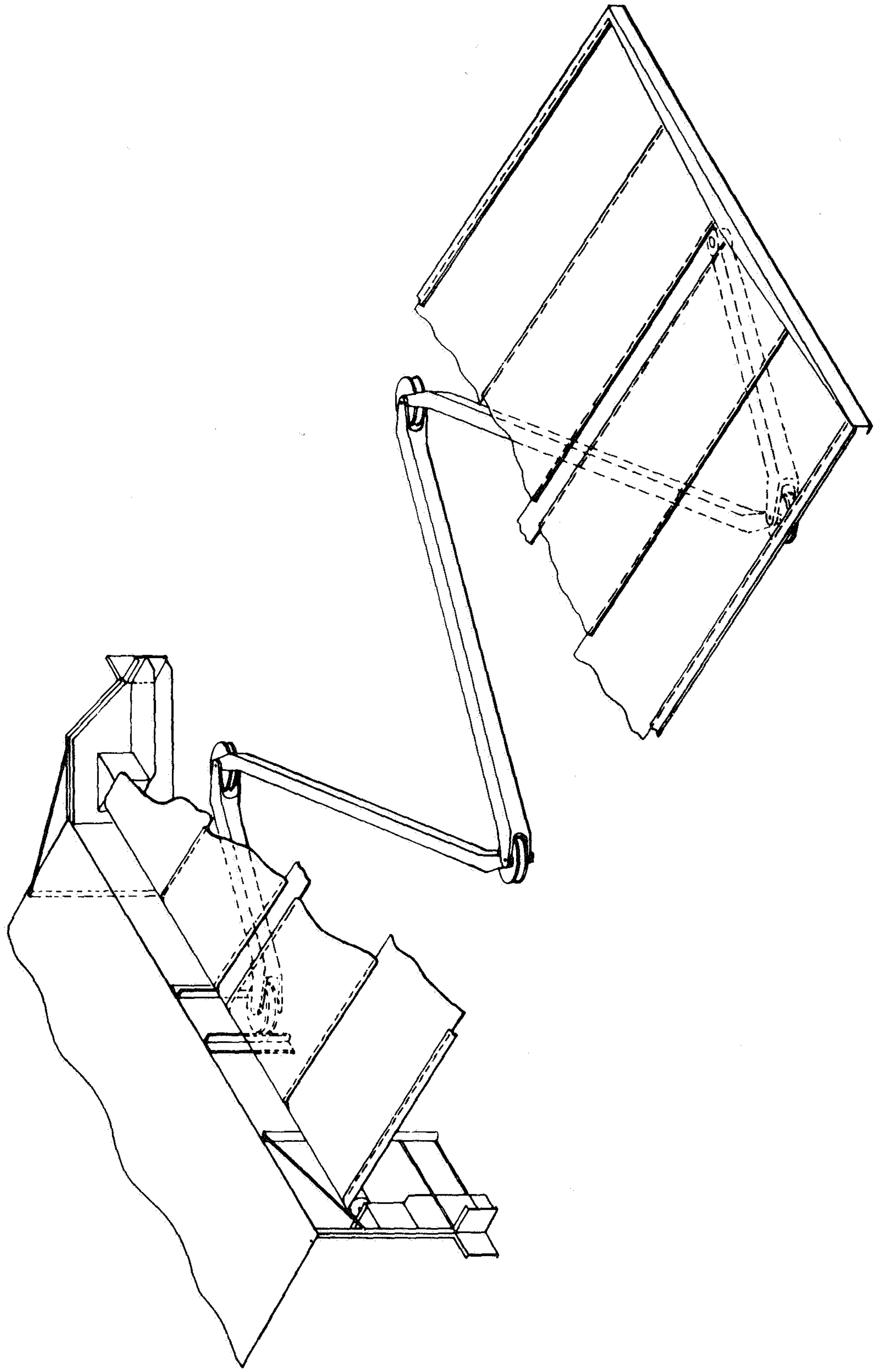


Figure 2.2.1-3

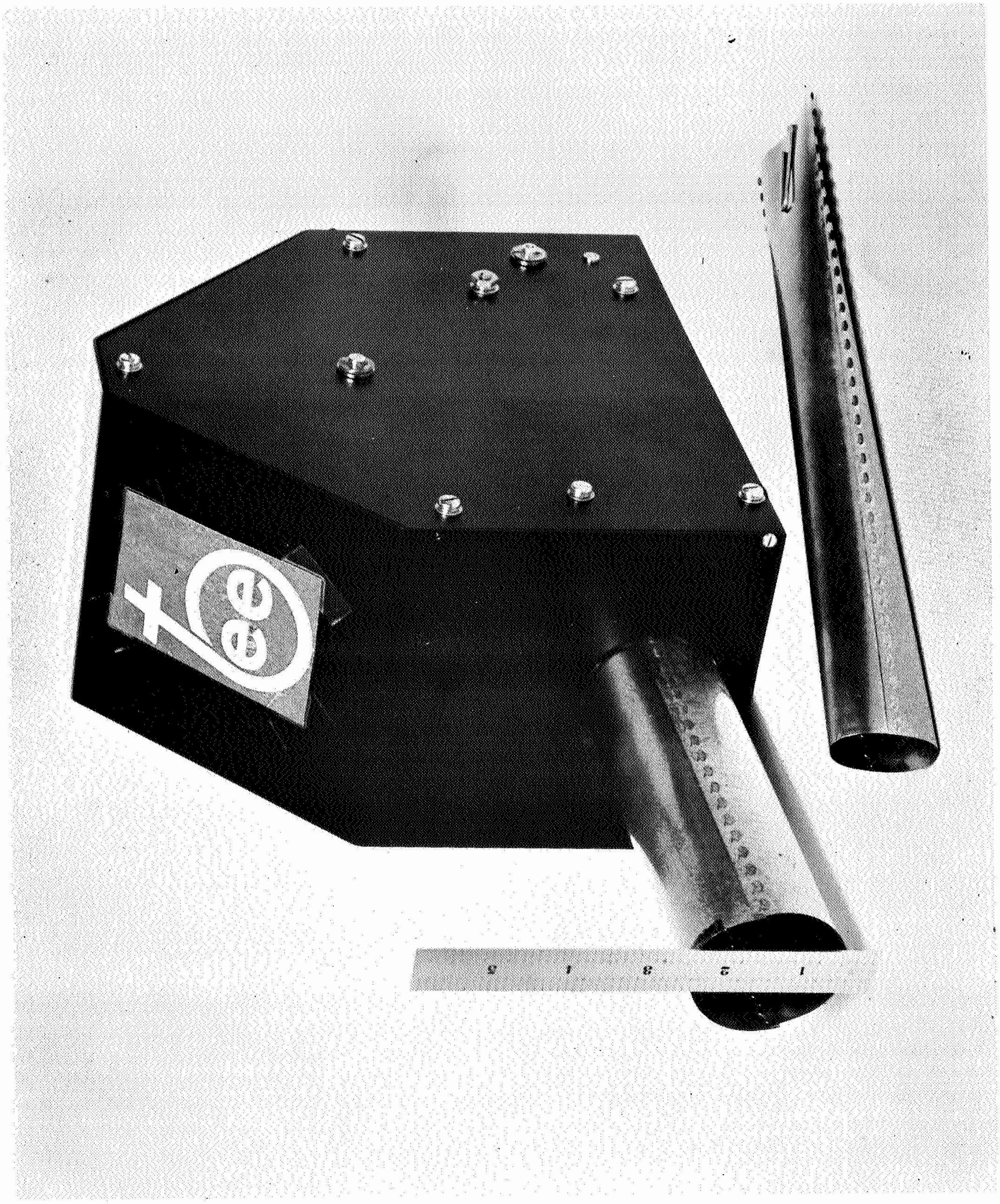


Figure 2.2.1-4

2.3 DESIGN DESCRIPTION

2.3.1 Structural System

Figure 2.2.1-3 presents a simplified pictorial of the supporting structure of the selected design. Figures 2.3.1-1 and 2.3.1-2 give major dimensions and general arrangement of the design. The array panel is stored on a drum during the launch mode. One end of the array panel is attached to the drum and the other end to a spreader bar located at the outboard end of a five element folding arm boom. The folding arm joints are programmed during their motion from the retracted to the deployed position by a cable system which interconnects the joints and programs them to insure that the motion of the pivot point, connecting the outboard arm element to the spreader bar, is a straight line function during deployment and retraction. During launch, the five arm elements and the spreader bar at the outboard tip, are retained between two end brackets (which are attached to the spacecraft body) and supported thereby against launch loads. Upon initiation of the first deployment cycle, pyrotechnic activated retaining bolts are released, permitting the deployment system to be extended.

The array panel consists of four subpanels and each subpanel of twelve identical modules. Each subpanel has its own power collection harness with the outboard panels having their harnesses located on the outboard edges of these subpanels and the two inboard subpanels dump their power into a common harness located between them. The module consists of a two mil Kapton substrate upon which 2 x 2cm x 8 mil thick, N on P, silicon solar cells, totalling 1290/module are mounted. The nominal area covered by solar cells is 277.4 square feet. Modules and power collection harnesses are mechanically interconnected to form one continuous panel. The end brackets are used to support all of the mechanism except the inboard end of the folding arm structure and the drive train, which are mounted directly to the spacecraft. Sway braces are used to transmit lateral loads to the mounting surface of the spacecraft. The arm tube elements, contain end fittings for pivot shaft and cable pulley mounting.

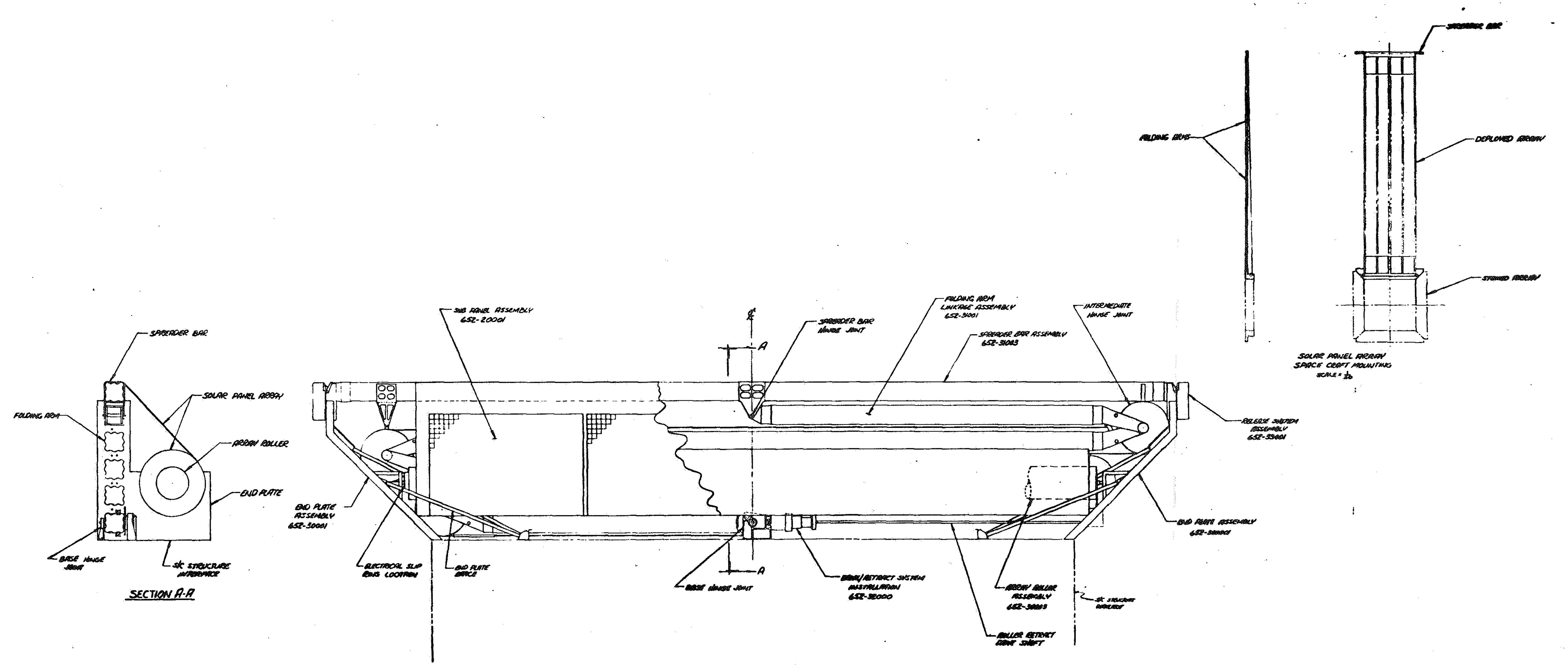


Figure 2.3.1-1 Solar Panel Array Assembly

FOLDOUT FRAME 1

FOLDOUT FRAME 2

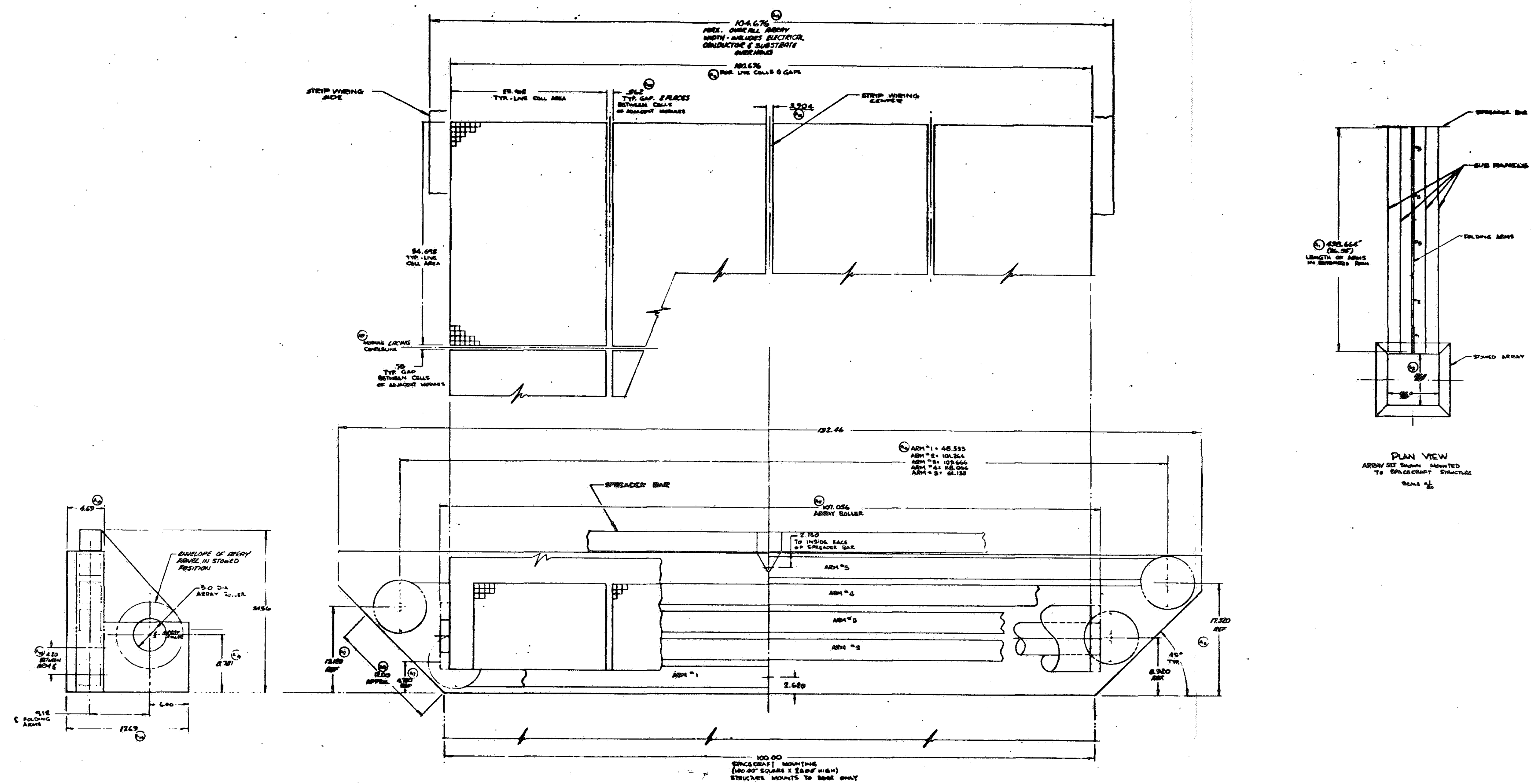


Figure 2.3.1-2 Solar Array Master Lines Drawing

During the course of the design studies, it was determined that the optimum power/weight ratio configuration for a total array set, consisting of 4 arrays, or a total of 1,000 square feet, would be obtained by having two adjacent 250 square foot arrays share a common end bracket. This approach has been selected for the design.

2.3.1.1 Array Roller

Intensive investigation, both by analysis and test as reported in the Second Quarterly Report (Fairchild Hiller document 652-00102-QR), indicated that the optimum Array Roller diameter is approximately 5 inches. It was also established that a drum type roller with end supports only would adequately sustain all anticipated loads without degradation to the system.

The design concept of the Array Roller, depicted in Figure 2.3.1-3, was selected based on the above facts. The roller consists of a graphite/epoxy cylinder 5 inches in diameter with a wall thickness of .027". End caps of aluminum, machined and then chemically milled to obtain very thin walls, are used to stabilize the ends of the Array Roller and transmit loads from the roller to a center shaft and thence to the endplates. Local reinforcing layers of graphite/epoxy material are added to the roller near the roller ends to provide the necessary bearing area for load transfer between the roller and end caps which are riveted together. Reinforcements of fiberglass cloth may be used in lieu of the extra layers of graphite/epoxy.

Independent shafts, mounted in the bearings of each End Plate, are used to support the roller at its respective hub. Each shaft has a threaded end which is screwed into the hub and is locked to the roller by means of a self locking plate nut affixed to the hub.

The roller is driven by an aluminum sprocket attached with screws to one of the hubs.

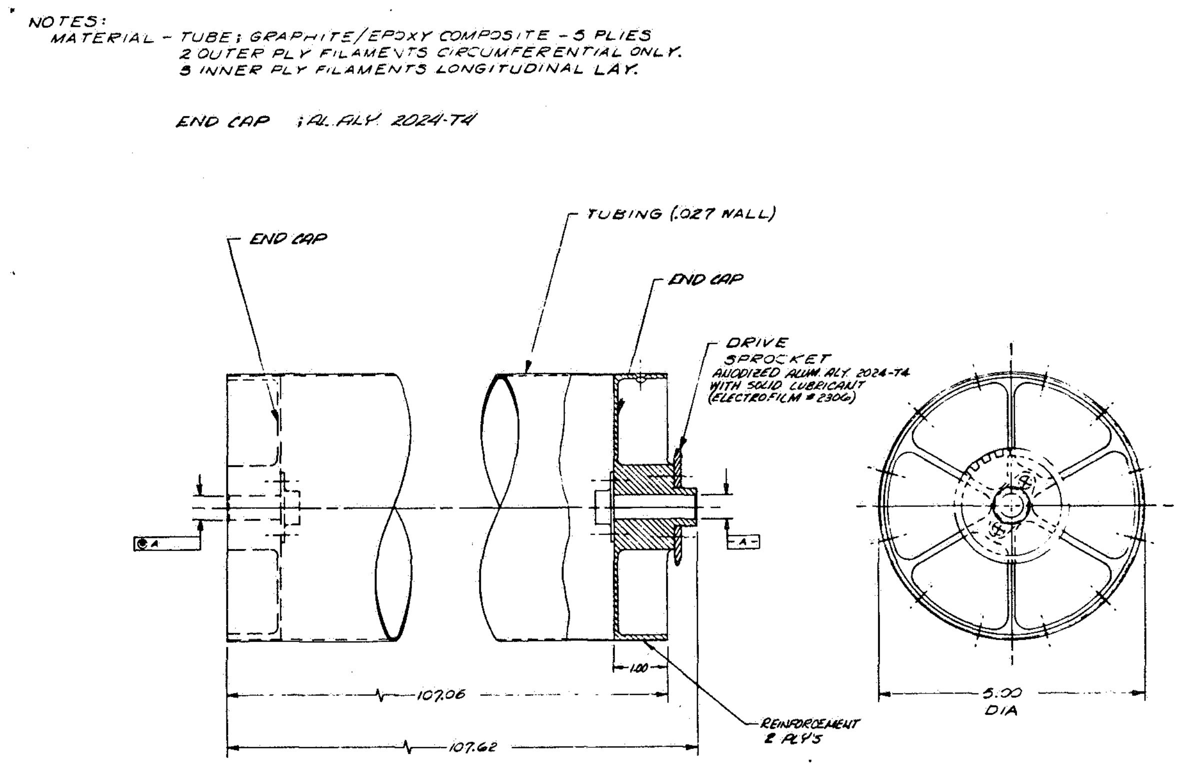


Figure 2.3.1-3 Array Roller

2.3.1.2 Linkage Assembly

The Linkage Assembly, consisting of the folding arms, arm fittings, pulleys, spreader bar and cables, is illustrated in Figure 2.3.1-4 and 2.3.1-5. The linkage system selected for deployment of the array is the five (5) element folding arm technique as described in Ref. 3. Although the linkage assembly performs kinematic activities, it also is a structural system and, as such, is included in this subsection.

Folding Arms

The Folding Arms portion of the linkage assembly consists of three (3) full length arms and two (2) half length arms. The half length arms are the end members of the folding arm linkage with the full length arms in between. The outboard half link is pinned to the spreader bar which pulls out the array; the other is pinned to the structure and acts as a driver for the linkage.

Each arm consists of a tube with beryllium fittings in each end to support the hinge pins and, where applicable, the pulleys and associated cabling. The tubes are fabricated from two layers of boron filament/epoxy composite material, with corrugated walls as shown in Figure 2.3.1-6. They form a 3 inch by 3 inch envelope with a .011 wall made up of two laminating layers. A transition piece approximately 3 inches long, which adapts the corrugated tube to the square ended arm fittings, is bonded between each of the fitting and tubes and is fabricated of boron filament/epoxy materials. The adhesive selected for this application is HT424 (Bloomingdale Rubber Co.) or equivalent.

Arm Fitting

The arm fittings, fabricated from beryllium (Berylco HP20 or equivalent), house the shafts and associated hardware necessary to support the pulleys. The fitting is made in two halves which are bonded together (HT424 adhesive) using a beryllium tie strap of Berylco PR-20 or equivalent. The arm fittings are so designed that all fittings are identical, thereby maintaining a minimum inventory.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

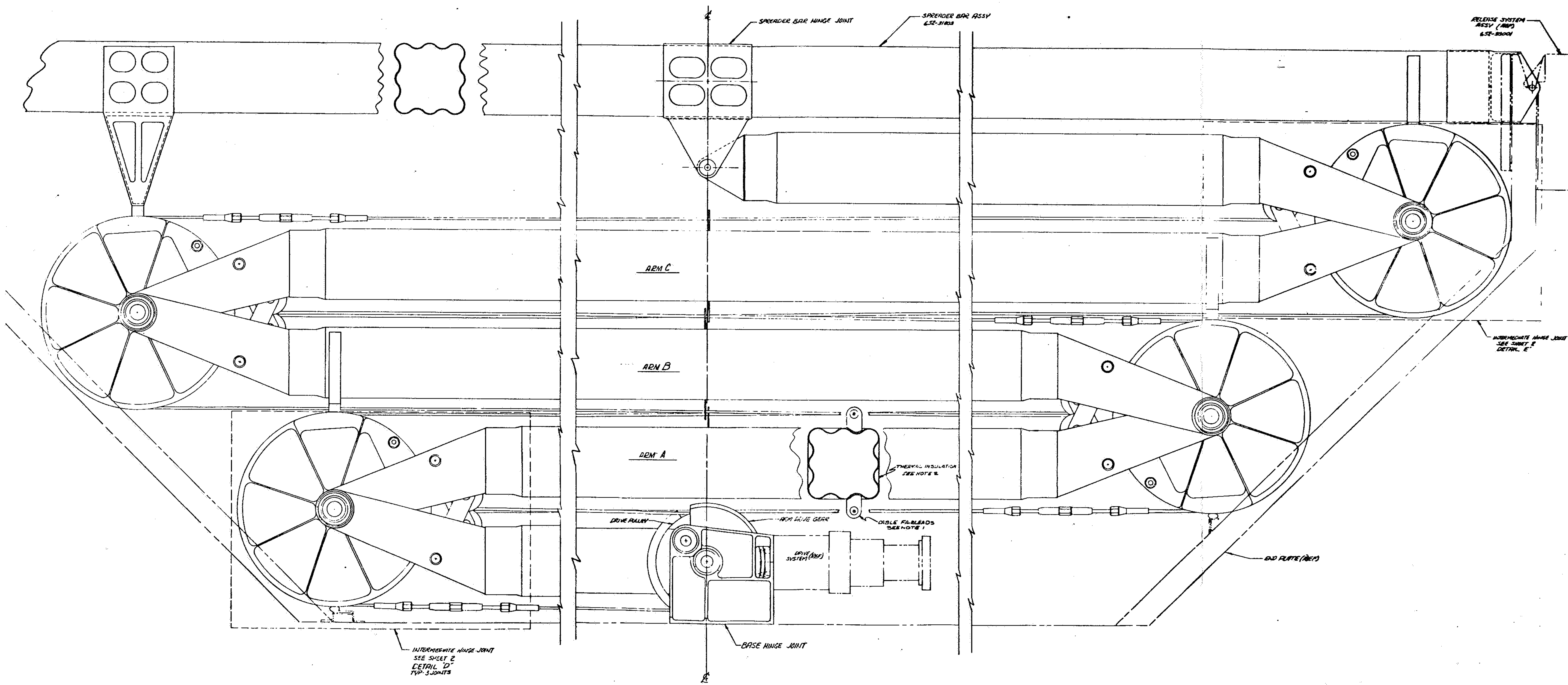


Figure 2.3.1-4 Folding Arm Linkage Assembly

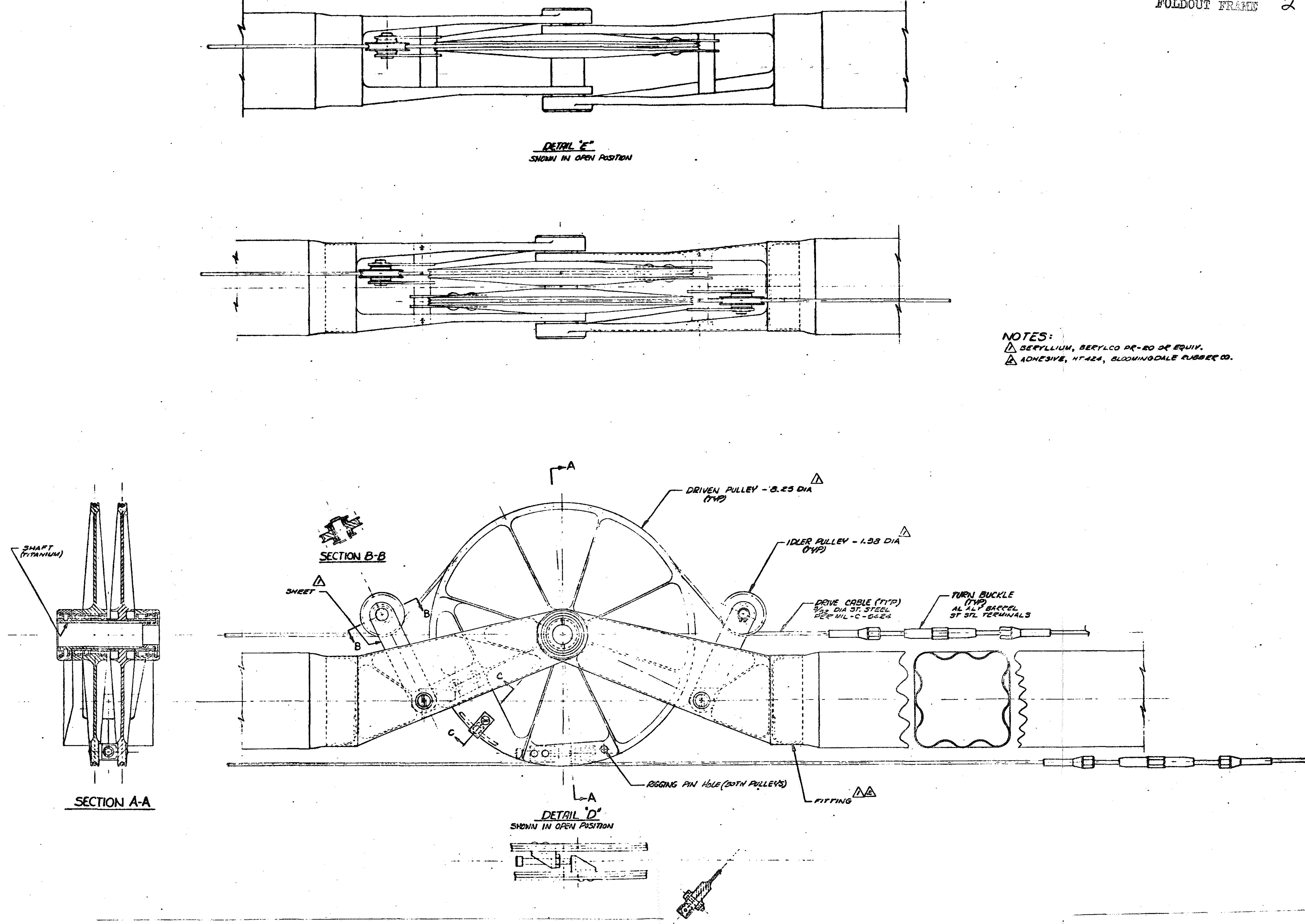
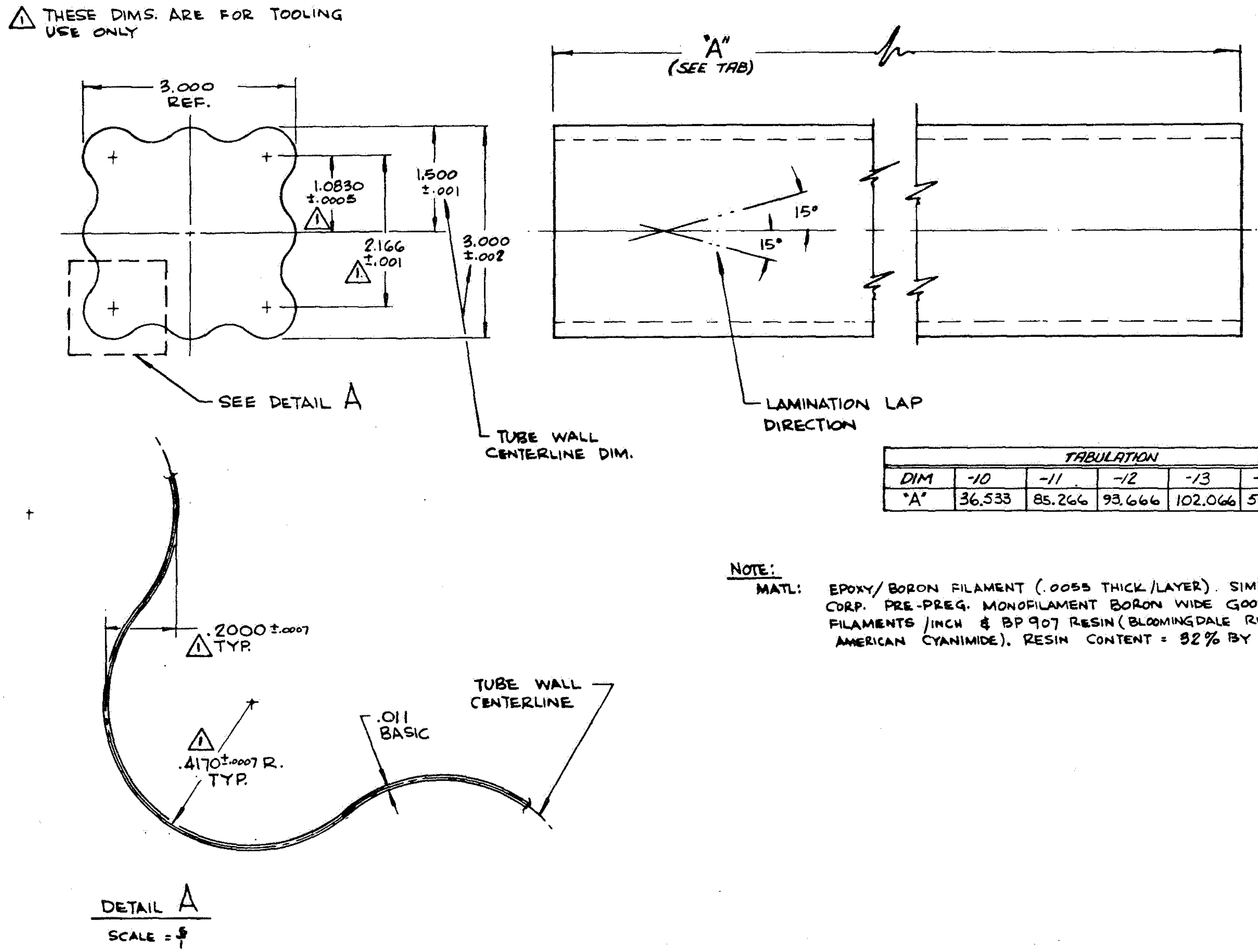


Figure 2.3.1-5 Folding Arm Linkage Joint Assembly



TABULATION						
DIM	-10	-11	-12	-13	-14	-15
"A"	36.533	85.266	93.666	102.066	50.133	128.466

NOTE:
MATL: EPOXY/BORON FILAMENT (.0055 THICK/LAYER). SIMILAR TO HERCULES CORP. PRE-PREG. MONOFILAMENT BORON WIDE GOODS, USING 216 FILAMENTS /INCH & BP 907 RESIN (BLOOMINGDALE RUBBER DIV. OF AMERICAN CYANIMIDE). RESIN CONTENT = 32% BY WEIGHT (NOMINAL)

Figure 2.3.1-6 Folding Arm Beam

Pulleys and Cables

The pulleys are fabricated from Berylco HP20 or equivalent beryllium. Linkage drive cables are attached to and act on the pulleys to control the joint motion. The joint design uses a minimum number of bearings by locking the shaft to one arm link. Bearings are then used only on parts which must rotate about the shaft. Joint rotation "stops" are mounted on the two pulleys at each joint to obtain correct position when fully open.

Rigging pins are employed for positioning the pulleys during cable adjustment. An idler pulley is affixed to the arm fitting to properly position the cable so that the necessary clearance is maintained between cables and arms in the retracted position.

Joints are locked in the fully open position by increasing cable tensioning progressively from outboard end to the spacecraft end of the folding arm. This procedure insures full open deployment of each joint and that each joint will remain in the full open position after deployment.

Positive mechanical joints were considered and evaluated. The design of a positive lock which must operate only once, i.e., upon initial deployment, is quite simple and highly reliable. But the requirement for multiple extension/retraction capability dictates a lock design capable of being unlocked upon command. Unlocking designs include mechanical or electrical solenoid operation. Both systems involve added complexity and hence reduction in system reliability and increase in system weight. For these reasons, the positive mechanical lock was discarded and the joints held in the full open position by the cable tension only.

The cables are stainless steel aircraft type with adjustments for attaining proper tension provided by turnbuckles.

2.3.1-3 Spreader Bar

The spreader bar (Figure 2.3.1-7) is a tube similar in construction to the folding arms, and is affixed to the outboard end of the Linkage Assembly.

The use of beryllium and aluminum as well as boron/epoxy composite material were evaluated for this application. The boron/epoxy composite is selected on the basis of strength/weight and stiffness/weight. Stiffness is important to hold deflections to a minimum and thereby maintain relatively even tension loading of the substrate. Launch loads induce higher design loads since the spreader bar restrains the folding arm elements against lateral motion in this mode.

When driven out by the Linkage Assembly, the spreader bar drags the array panel off its roller into the deployed configuration. A band fitting at the center of the spreader bar acts as a hinge joint for connection to the outboard arm link. A pulley rest is located near the end of each link for snubbing the pulleys into place in the retracted condition. End caps at each end of the spreader bar form an end closure, provide stiffness to the bar, and support a latch pin or plate used to snub the Linkage Assembly during the launch mode.

2.3.1.4 End Plate

The End Plates (Figure 2.3.1-8 and 2.3.1-9) provide support for the array assembly and tie it to the vehicle structure. Provisions are made on the End Plates to support the Array Roller, Drive System, Spreader Bar and the Pulleys.

A bracket, housing the bearing that supports the Array Roller, is mounted on the End Plate as is a fitting for supporting elements of the Drive System. Pulley guides and snubbers are mounted on the End Brackets to position pulleys and transfer folding arm system inertia loads to the base structure.

The figures depict the End Plates used for a single array system but can be easily modified by addition of brackets, etc. to support two adjacent arrays. In such a design, the End Plates are a combination of the left and right hand parts as shown in the figure. The web and most of the stiffeners which are common to both

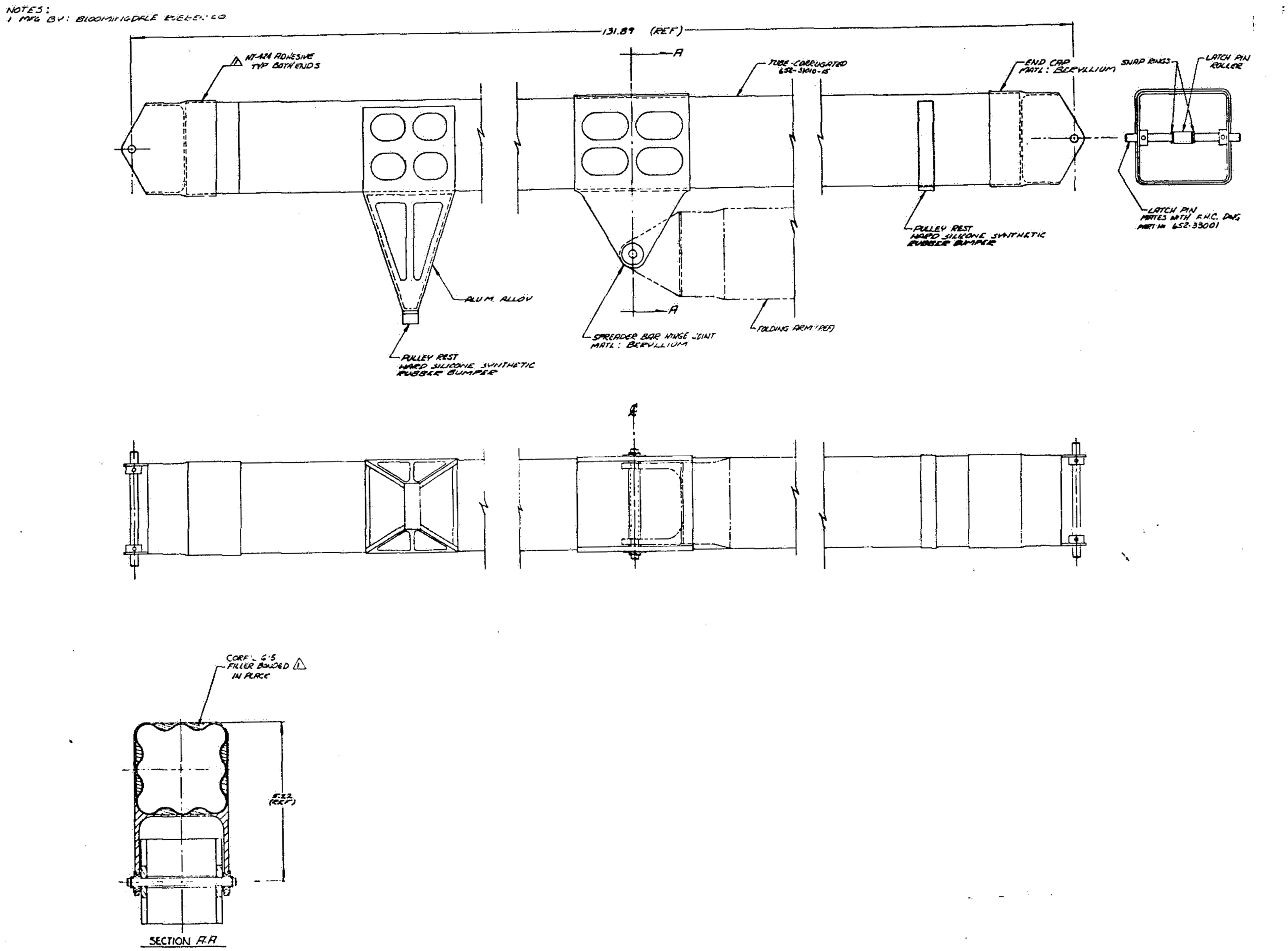


Figure 2.3.1-7 Spreader Bar Assembly

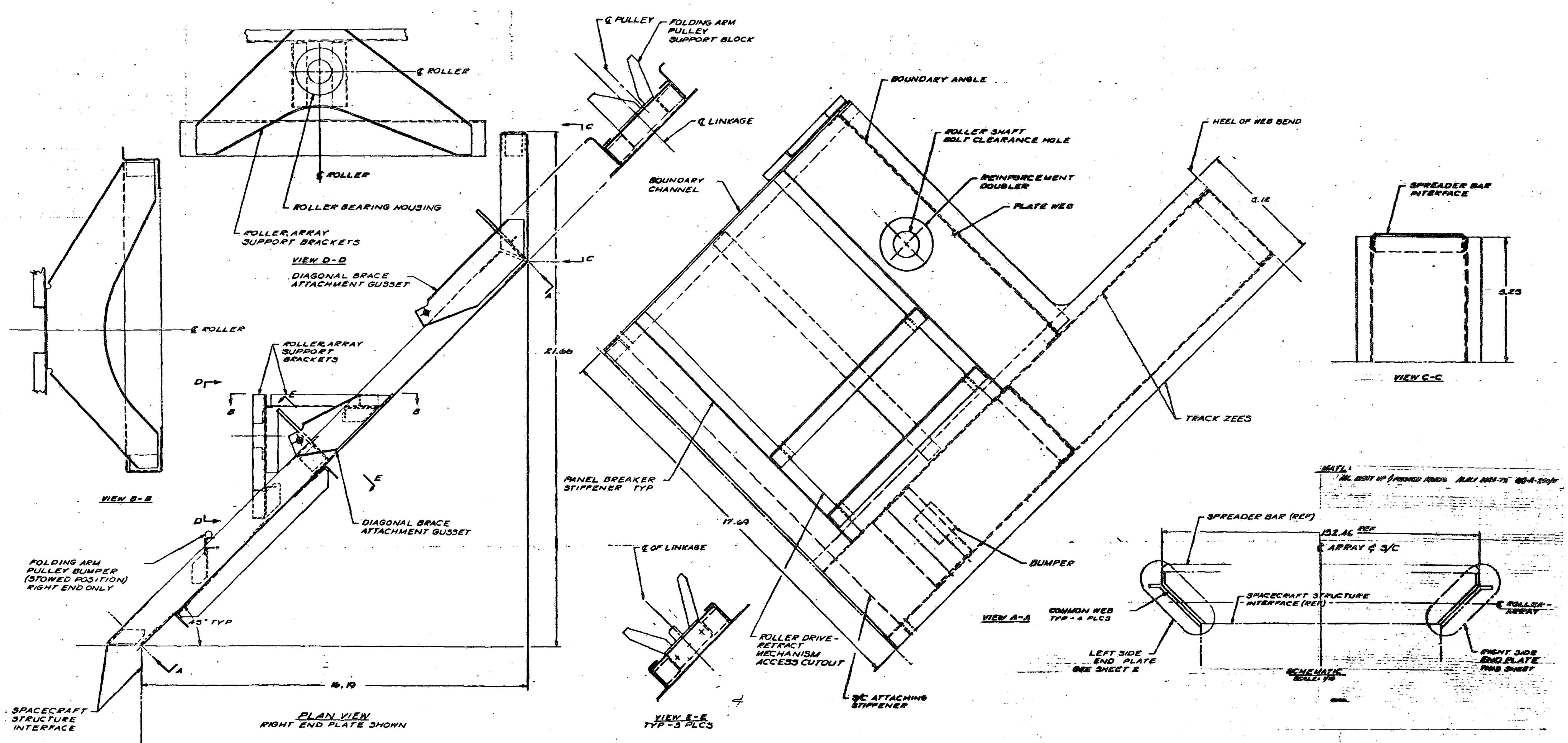


Figure 2.3.1-8 End Plate Assembly

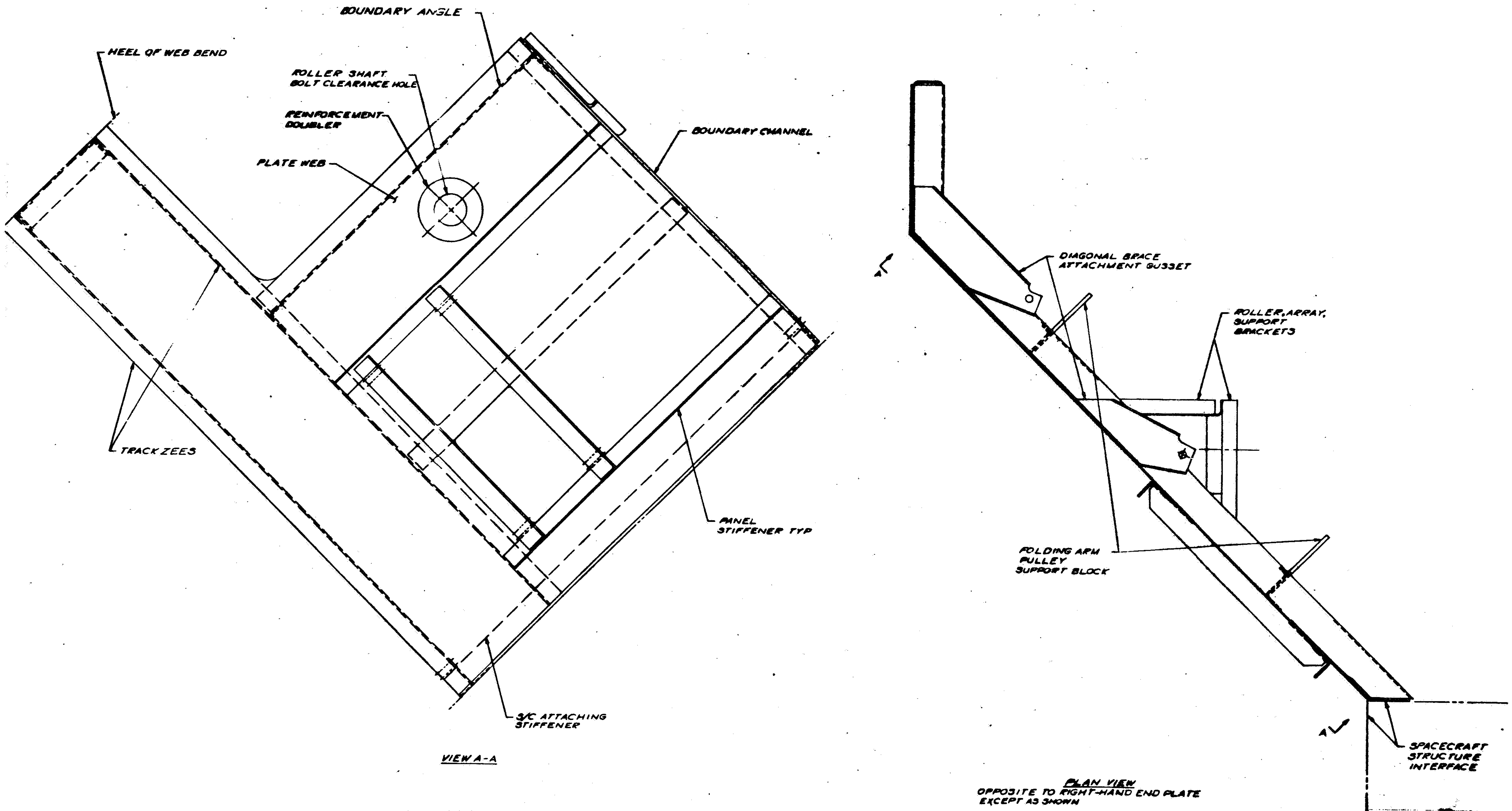


Figure 2.3.1-9 End Plate Assembly

End Plates would be shared, not duplicated, since the existing design is strong enough for the combined loads from two adjacent arrays.

For the design shown, a weight saving of 2.3 lbs. (about 50%) can be realized by substituting a graphite/epoxy composite material for the aluminum. The use of this material in this application will require some redesign to incorporate integral stiffeners, bosses, and possible brackets. Graphite/epoxy composites are quite new with limited experience in their application in complexly loaded structures. Therefore, such a design as postulated must be thoroughly analyzed, fabricated, and tested before its use in this application can be recommended.

2.3.2 Mechanical Components

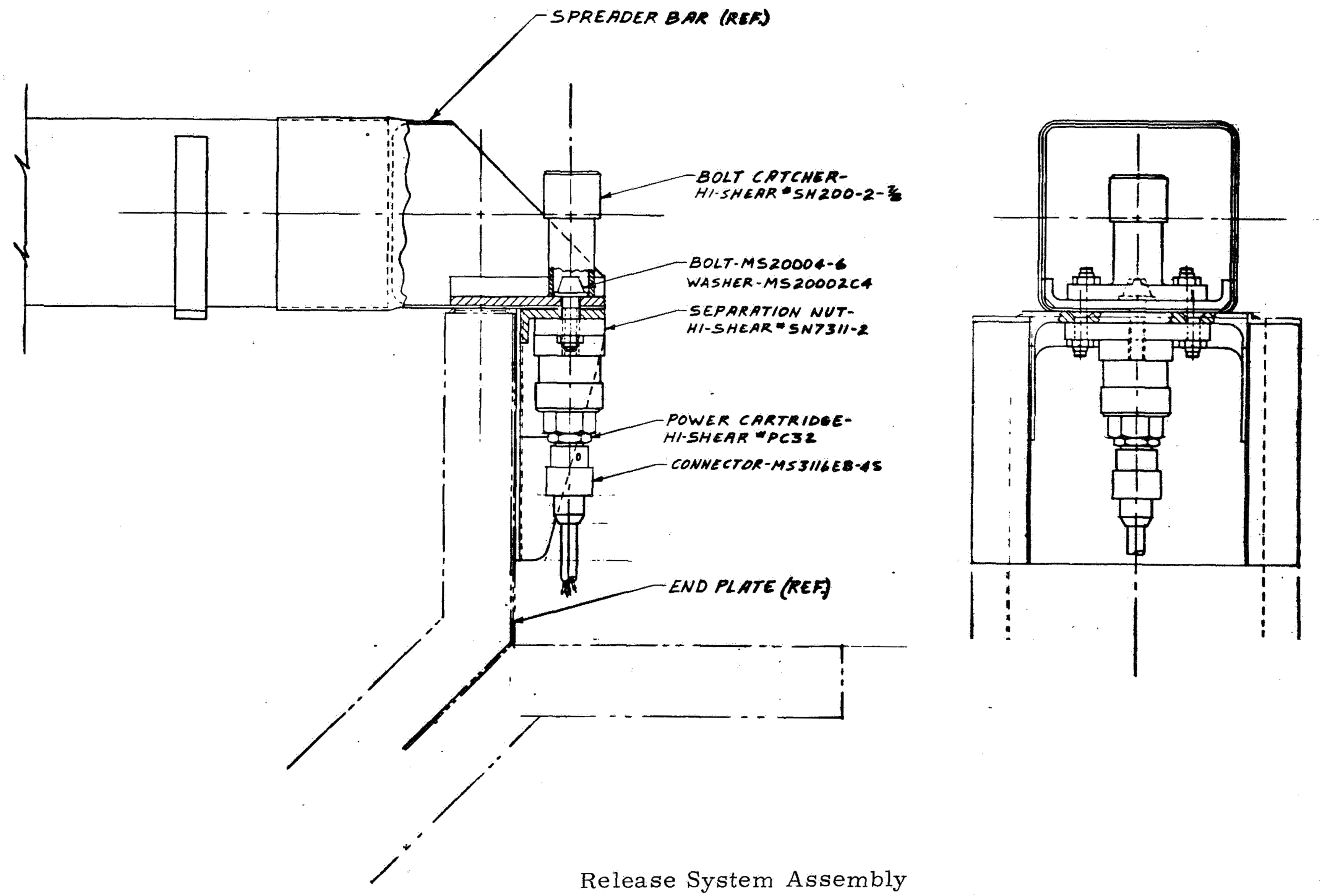
The mechanical components of the design include the folding arm or linkage system, the launch latch and release sub-system, and the drive train assembly. The linkage system is described in section 2.3.1.2.

2.3.2.1 Release System

The Release System unlatches the Linkage Assembly subsequent to the launch mode. Two methods of release were considered; a solenoid, operated latch and an explosive bolt. (Figure 2.3.2-1). The explosive bolt method is simpler and requires only a tie plate which separates upon release but does not have relatching capability in space. This is not considered a disadvantage, however, since anticipated loads on the array during potential missions, and with the array retracted after initial deployment, are expected to be of such a magnitude that the Linkage Assembly is easily capable of sustaining such loads without being latched in the retract position.

2.3.2.2 Drive System

The Drive System is shown pictorially in Figure 2.3.2-2 and an installation drawing is reproduced in Figure 2.3.2-3. Motive power for the differential drive/retract system is supplied by a small D.C. gearmotor. The differential unit splits the drive/retract system into two drive trains; one drives the inboard folding



Release System Assembly

Figure 2.3.2-1

DRIVE SYSTEM CONCEPT

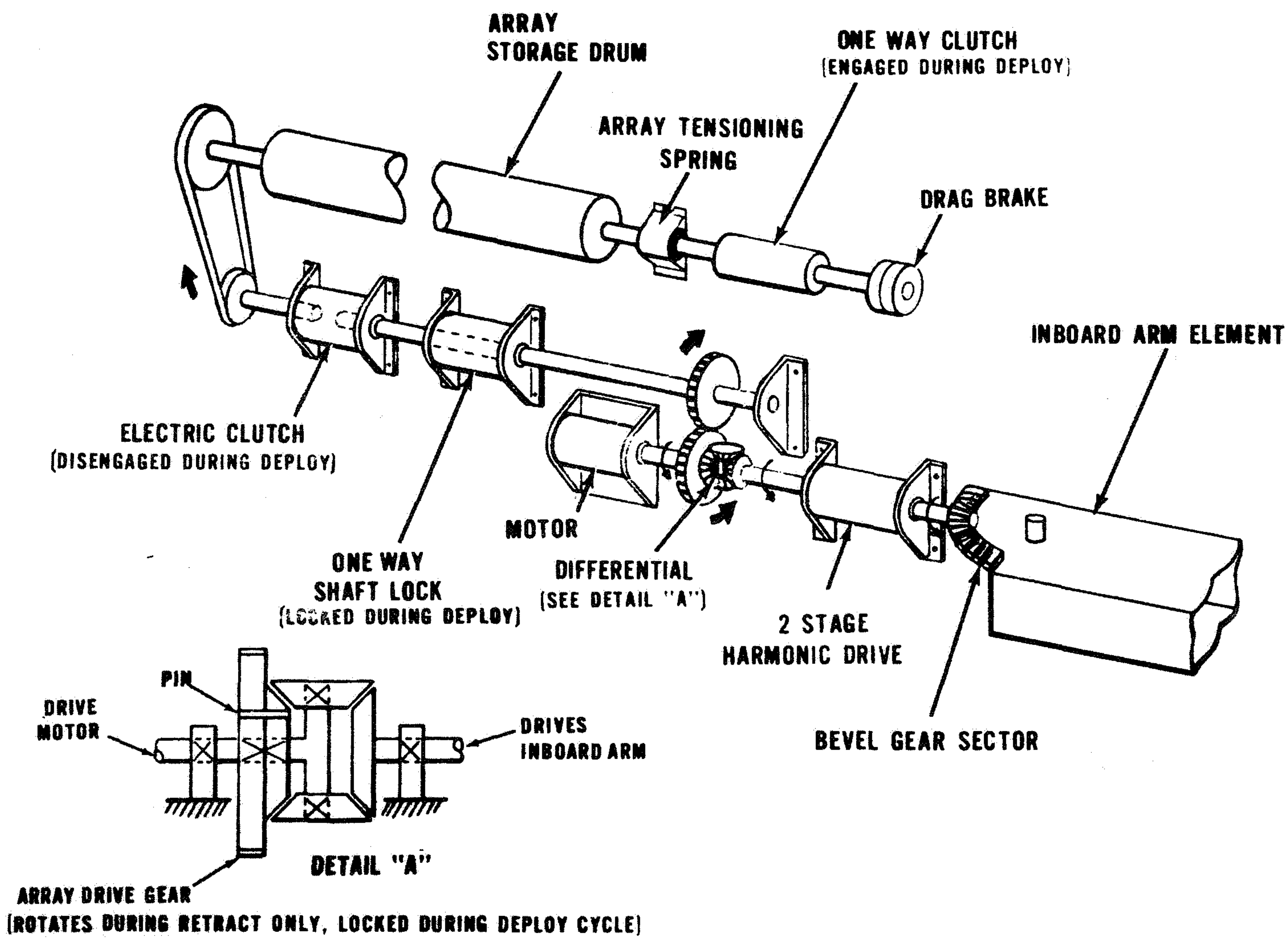


Figure 2.3.2-2

FOLDOUT FRAME 1

FOLDOUT FRAME 2

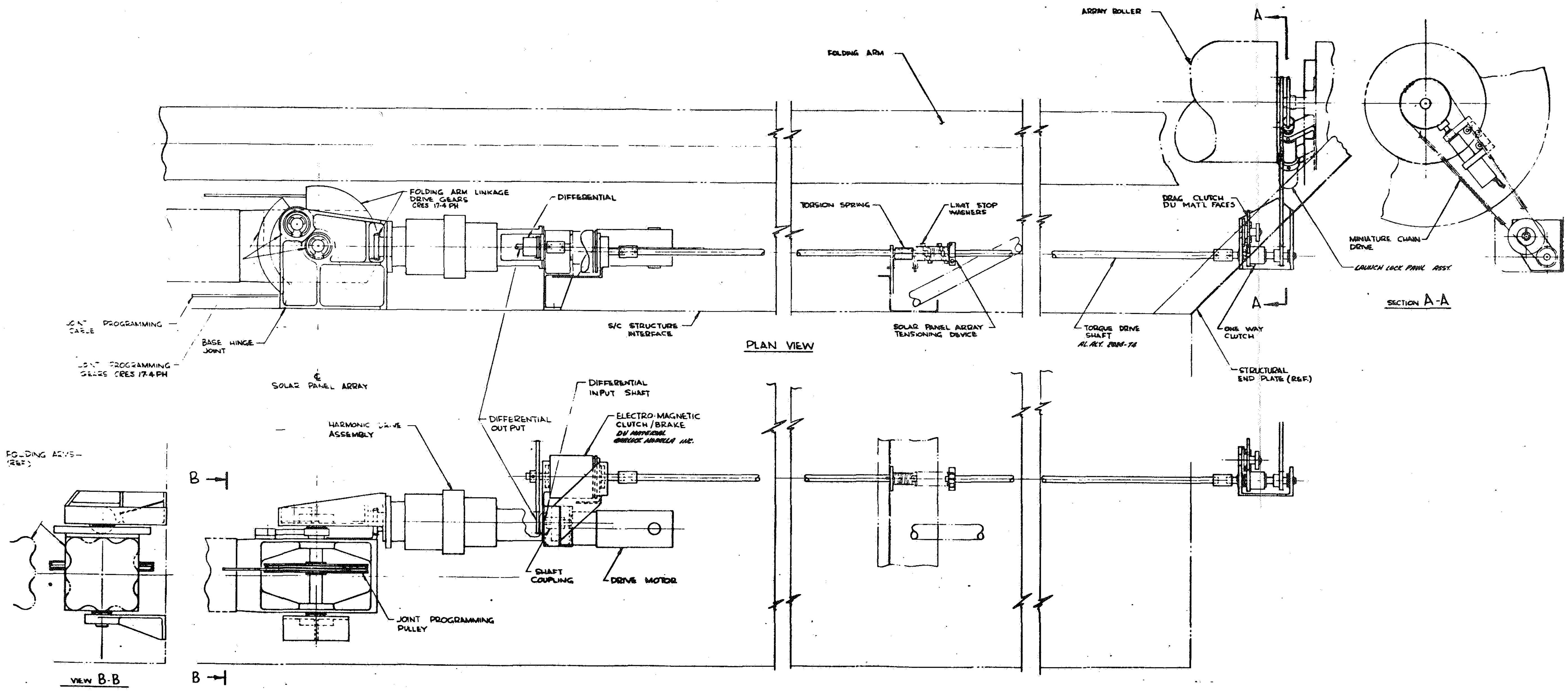


Figure 2.3.2-3 Drive System Installation

arm and activates the folding arm linkage for both deployment and retract modes; the second drive train applies torque to the array roller during the retraction mode only.

With the electromagnetic clutch/brake de-energized, the clutch input shaft (differential side) is locked to the clutch housing; therefore the clutch input shaft cannot rotate and the entire output of the differential drive is used to extend the Linkage Assembly. The clutch output shaft (array roller side) is free-floating, thus allowing the array roller to rotate as the solar panel array is deployed. Resistance to rotation of the storage roller only during deployment is controlled by a drag brake actuated through a one way clutch.

Deployment Mode

One differential output gear is connected to the clutch/brake input shaft which is locked to the clutch/brake housing and prevents shaft rotation.

The other differential output gear is connected to the input shaft (wave generator) of the two stage harmonic drive unit. The harmonic drive unit contains an 8, 000:1 reduction ratio which decreases the drive motor speed but increases the torque sufficiently to drive the folding arm linkage. The output shaft (flexible spline) of the harmonic drive unit is connected to a bevel gear pinion which meshes with a bevel gear sector attached to the inboard folding arm.

When the D.C. gear motor is energized, it drives through the differential, the harmonic drive and the bevel gears and rotates the inboard folding arm. The deploying action of the folding arm pulls the panel off the roller. The rotation of the array storage roller shaft actuates a one way clutch which is connected to a friction (drag) brake. The braking effect creates enough tension in the array substrate to prevent billowing during deployment.

During the last revolution of the array roller, a torsion spring is engaged. This torsion spring tends to retract the deployed array panel; this maintains a tension in the array panel after deactivation of the drive system.

Retraction Mode

During the retraction mode, the D. C. gearmotor is reversed and the inboard folding arm is retracted. The electromagnetic clutch/brake is energized and couples the input and output shaft of the clutch. This removes the brake resistance from the array roller side of the differential. At the same time, the one way and the friction clutches are disengaged, thus removing all braking forces from the storage roller. With all the controlled resistance removed from the system, a driving torque is transmitted from the differential through the clutch/brake and to the array roller shaft. The array panel tensioning torsion spring aids in retraction for the first half revolution of the array roller and then is disengaged. The higher friction of the arm drive system assures that sufficient force is applied to the storage roller to maintain proper tension in the substrate as it is retracted and rewound on the roller.

The differential unit provides simultaneous retraction of the folding arm linkage and roll up of the solar array panel.

2.3.3 Electrical System

The electrical system for the design is composed of the solar cell modules, the power collection harness, the slip ring assembly for transferring power across the storage drum/end bracket rotating joint, wiring harnesses for providing the launch lock release explosive bolts with initiation power, and current to the drive motor and magnetic clutch.

The slip ring assembly, while important, is not of primary concern in this study. Several space qualified designs are available as models, for example, the Nimbus Solar Array slip ring assemblies. A unit of suitable size can be designed and therefore, no further consideration is given to this component. The wiring harnesses to the explosive bolts, motor, and magnetic clutch are of conventional hardware design. The following paragraphs describe the Solar Array Panel and collection harness of the selected design.

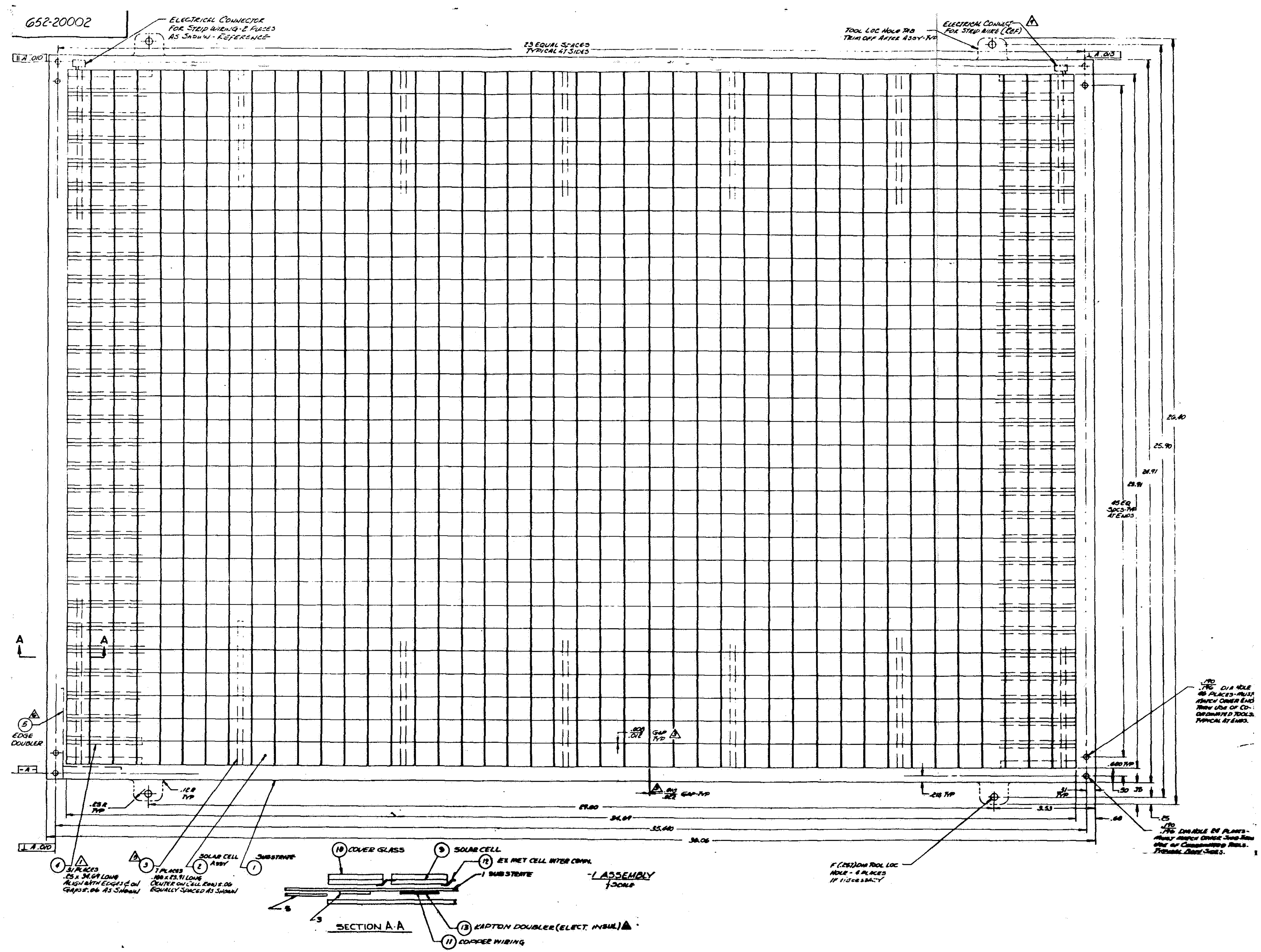


Figure 2.3.3-1 Panel Module Assembly

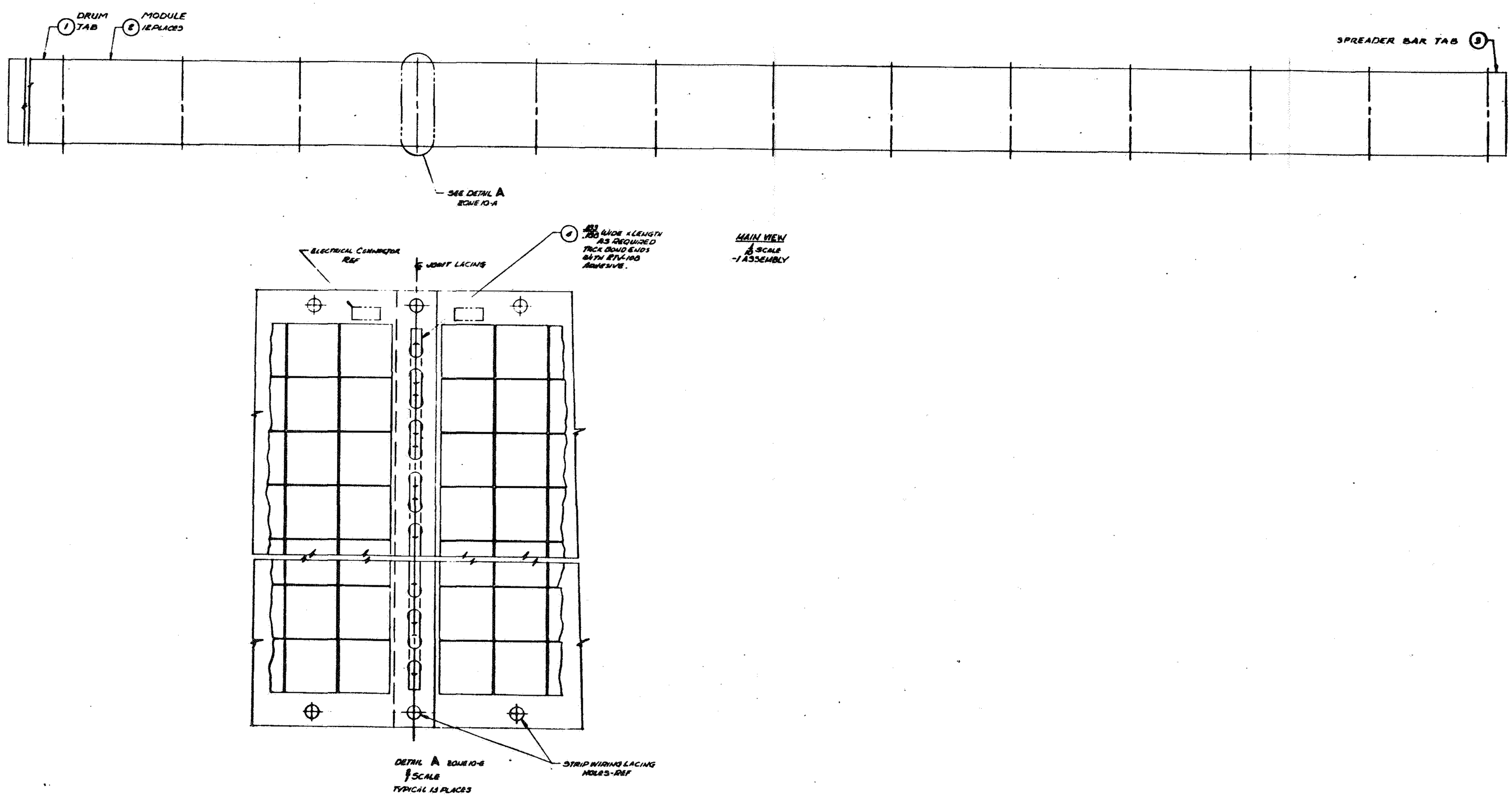


Figure 2.3.3-2 Sub Panel Assembly

NOTES:
1. INTERPRET GEOMETRIC TOLERANCES PER ASA Y14.5.
2. 6 MIL COPPER STRIPS x .026 WIDE WITH .030 GAPS 2 LAYERS BONDED TO 1.5 MIL KAPTON "F" FILM WITH 1 MIL KAPTON "H" COVER LAYER USING RTV 108 (GE) ADH. SIDE STRIP TO HAVE 24 WIRES PER LAYER WITH .50 LACING TAB. CENTER STRIP TO HAVE 48 WIRES PER LAYER WITH .50 LACING TAB ON BOTH EDGES.
3. CONNECTORS TO BE ADDED TO PICKUP CELL WIRING AT MODULE CORNERS.
4. MFG BY: ITT CANNON TYPE MTB

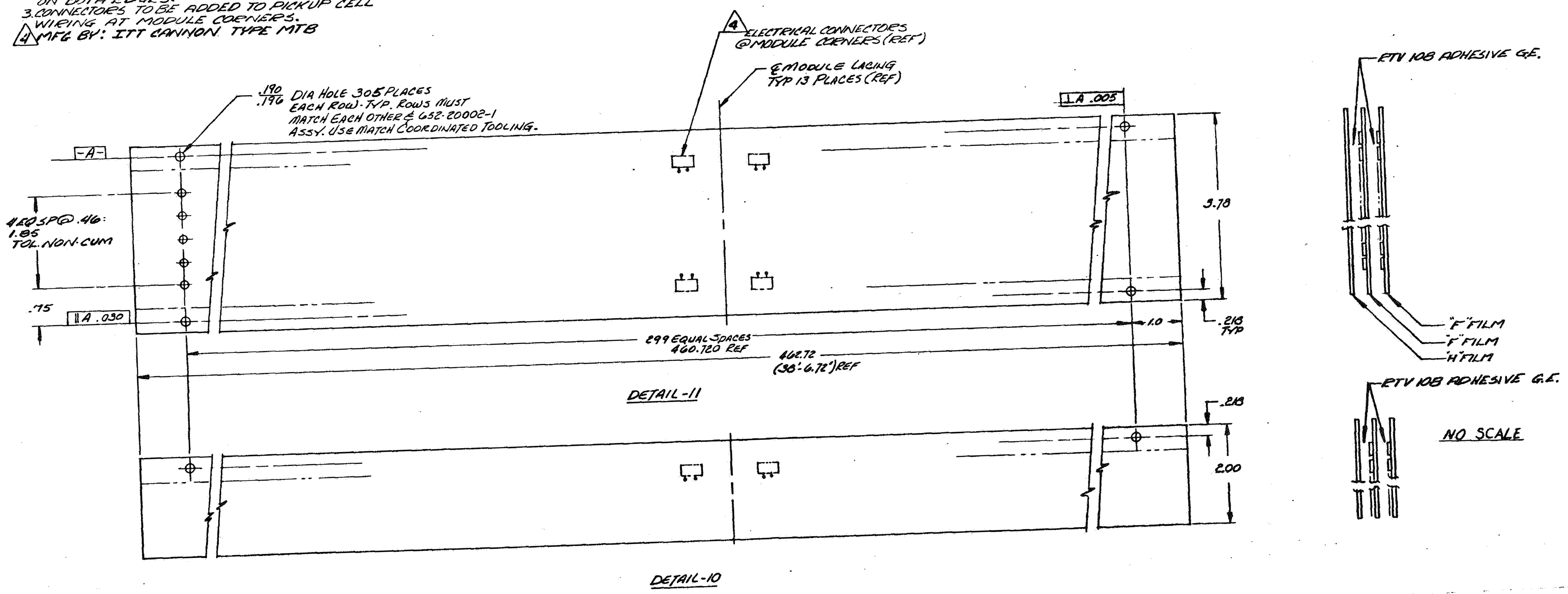


Figure 2.3.3-3 Strip Wiring Harness

2.3.3.1 Solar Array Panel

The Solar Array Panel (Figures 2.3.1-1 and 2.3.1-2 is composed of 48 individual and identical solar cell modules (Figure 2.3.3-1). Twelve modules are connected mechanically in series to form a subpanel (Figure 2.3.3-2). Four (4) subpanels, connected mechanically in a parallel arrangement with three wiring harnesses (Figure 2.3.3-3 and 2.3.3-4) are attached with Kapton tabs to the Spreader Bar and Storage Roller to form the total flexible panel surface.

Each of the 48 solar cell modules consists of 1,290 two centimeter square solar cells bonded to a Kapton H film substrate approximately 2 ft. wide by 3 ft. long. The solar cell submodules and strings are electrically interconnected by soldered 2 mil expanded silver mesh and ultimately terminate in two redundant connectors on the substrate which matewith connectors on the strip wiring. The substrate is provided with a hole pattern along the edges for lacing to the strip wiring and/or another substrate. All hole patterns are match co-ordinated to insure geometric alignment of subpanels and strip wiring.

The selected array configuration includes:

- Protection of the supporting arm structure from the direct rays of the sun, and hence better control of thermal deflection of the supporting system in the extended position.
- Using one interconnected sheet for the array panel, a more uniformed tension is obtained throughout the panel. This factor, coupled with the pivoted, free floating, spreader bar attachment to the boom, results in less chance of wrinkles or buckles in the panel occuring during the retraction cycle and roll up of the array panel on the storage drum.
- Tracking of the array panels during retraction is enhanced.

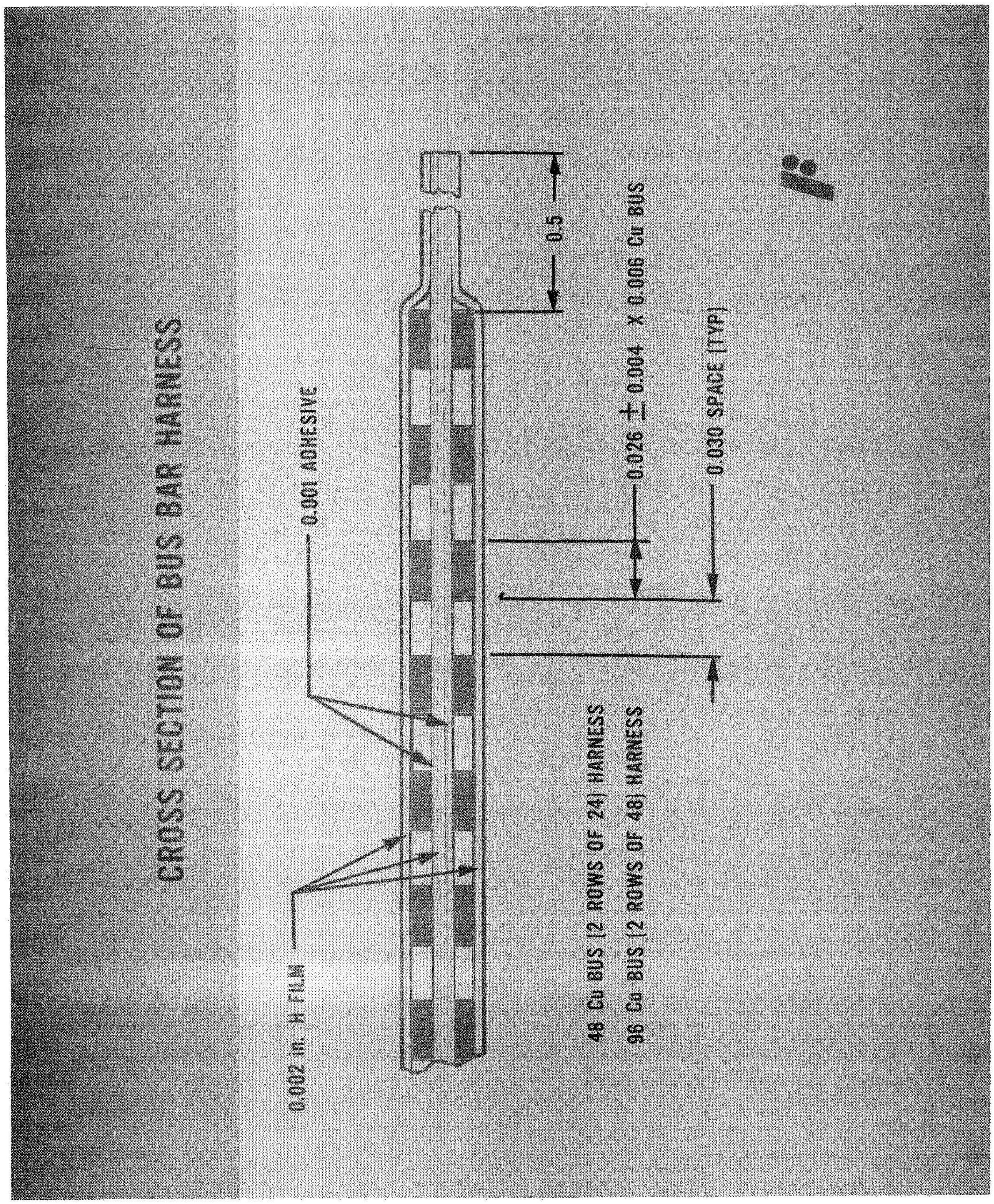

CROSS SECTION OF BUS BAR HARNESS
0.001 ADHESIVE
0.002 in. H FILM
0.5
0.026 ± 0.004 X 0.006 Cu BUS
0.030 SPACE (TYP)
48 Cu BUS (2 ROWS OF 24) HARNESS
96 Cu BUS (2 ROWS OF 48) HARNESS

Figure 2.3.3-4

- The modular construction of the arms and of the array panel permits rapid and easy replacement of reasonable size parts, if such is necessary.

Each module is stiffened laterally by bonding seven (7) .025" thick by .188" wide strips of magnesium alloy spaced equally on the back of the substrate and extending across the width of solar cells. Thirty one .032" thick by .187" wide polyurethane foam backing strips are bonded perpendicular to the stiffening strips, in line with the solar cell edges and extending the length of the cells for protective cushioning of the cells while being rolled on the array and during launch.

2.4 SUPPORTING ANALYSES

The analyses conducted in the various disciplines, i.e. design, structures, thermal, etc., are presented in detail in References 2, 3, 4 and 5. The following sections describe briefly the type of analyses conducted and summarize the results of these studies.

2.4.1 Design Studies

The design studies are concerned with generation of various conceptual designs for the total system and for the various components therein. A systematic investigation was conducted of those parameters which would aid in the selection of the optimum design of the 30 watt per lb. roll up solar array. Design concepts of the components of the total systems were formulated and evaluated for their functional capabilities; minimum weight and packaged volume as well as fabrication feasibility were the factors of prime consideration.

Panel Support Structure

The aspect ratio of the array panel (length/width) influences the number of elements required in the folding arm beam. The method of supporting these arms during the launch phase and the available packaging volume are other considerations. For the TEE and Hingelock tube approaches, packaging volumes were generated for nominal packaging, minimum packaging, and a design minimized the eccentricity of the load applied to the tube by the array panel. The results of these studies are summarized in Figure 2.4.1-1.

Design studies were also conducted of various other structural components:

- Panel Storage Roller
- Spreader Bar
- End Brackets and other base supporting structure
- Drive Train
- Folding arm joints and the associated programming mechanisms
- Launch lock and release mechanisms

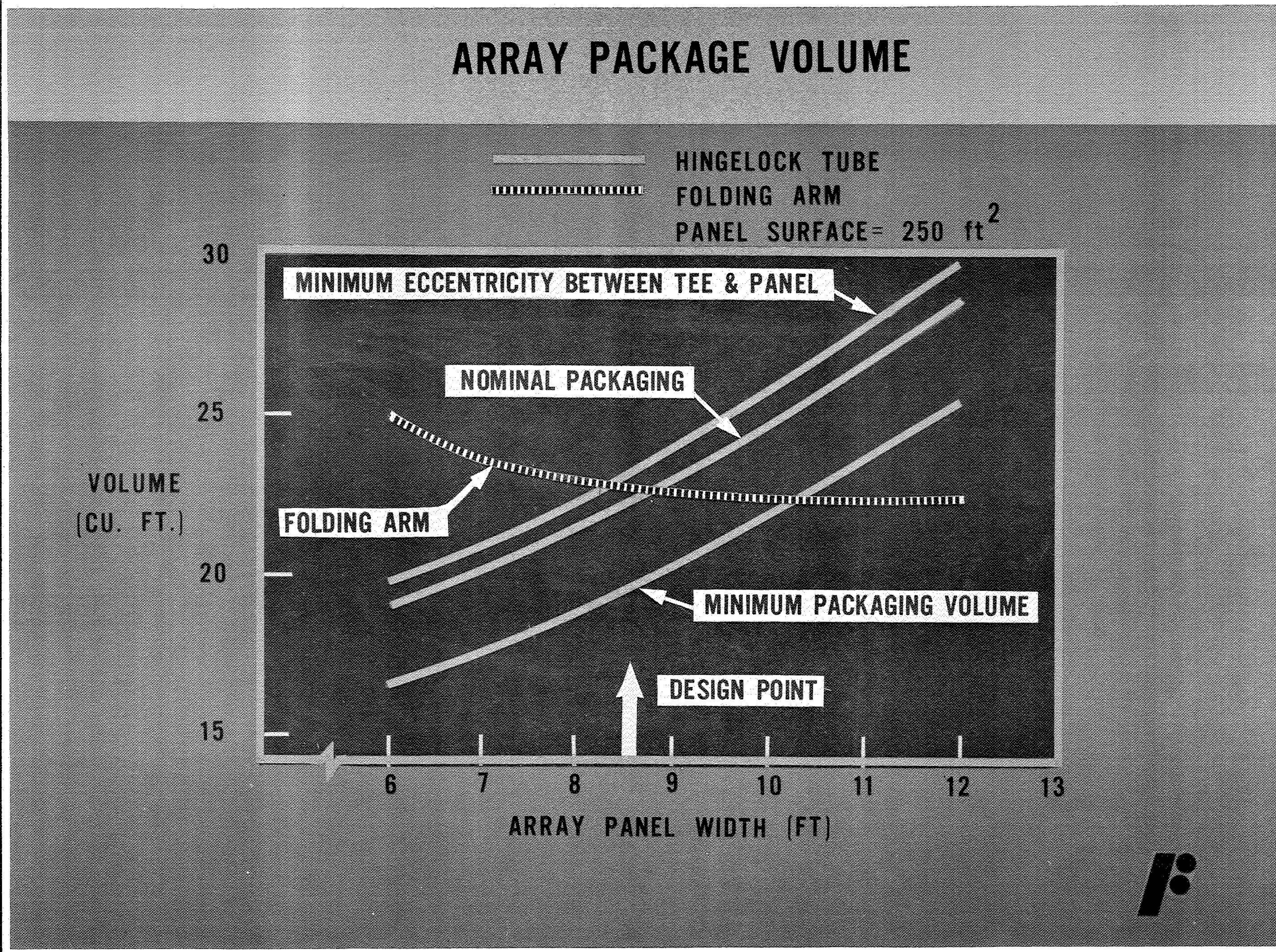

ARRAY PACKAGE VOLUME
HINGELOCK TUBE
FOLDING ARM
PANEL SURFACE = 250 ft^2
MINIMUM ECCENTRICITY BETWEEN TEE & PANEL
NOMINAL PACKAGING
FOLDING ARM
MINIMUM PACKAGING VOLUME
DESIGN POINT
VOLUME (CU. FT.)
30
25
20
15
6
7
8
9
10
11
12
13
ARRAY PANEL WIDTH (FT)

Figure 2.4.1-1

Panel Storage Roller

A total of 10 candidate configurations were generated for the panel storage roller ranging from a hollow tube to a solid foam tube. Various methods of supporting the tube internally were considered including spokes, bulk head supports, and stiffening rings. Thin wall tubes were considered along with honeycomb sandwich panel type tubes. A simple hollow tube with aluminum end caps, as described in Section 2.3, was selected.

Spreader Bar

Design concepts for the spreader bar included sheet metal, honeycomb sandwich panel, corrugated tubes, rigid polyurethane core with skins, and a machining or casting from metal. The corrugated tube, identical in cross-section to the folding arm tubes and fabricated from a boron/epoxy composite material was selected.

End Brackets

Various methods of construction for end brackets and other supporting structure were considered and evaluated with a standard sheet metal construction of aluminum alloys selected for the final design.

Drive System

The drive system for the extension and retraction of the folding arm systems, TEE devices, synchronizing systems where more than one supporting element is used, and the storage drum retract drive were designed conceptually and estimates made of the weight of the various components in order to obtain a comparison. Design of the drive system details was accomplished only upon selection of the baseline design and the components therein were optimized as the design proceeded.

Folding Arm Joint

Two methods of controlling the joint motion of the folding arm beam system were considered. One used a planetary gear train at each joint; the second used direct coupling of the cable pulleys to the folding arm elements. The latter system was selected as being lighter in weight, simpler, and more reliable although somewhat larger in overall dimensions.

Two mechanical folding arm linkage design concepts were formulated and evaluated. They are:

- Tubular single link
- Scissors linkage

Weight trade-off comparisons of these two systems resulted in selection of the tubular single link system.

The two TEE configurations investigated were:

- Overlapping tubular element (TEE). Two of these elements, located at each side of the array, were employed primarily to obtain torsional stiffness of the deployed system. Thus, dual drive systems and a synchronizing mechanism between such systems were required.

- A Hingelock collapsing tubular element. A single element, located at the center of the array, provided the necessary structural rigidity for this concept.

Both of these configurations, together with the folding arm system, were evaluated to determine which system resulted in a maximum power/weight ratio for the solar array design. Although the Hingelock tube system is slightly lighter than the folding arm system, the latter is selected because the Hingelock tube is not considered 1968 state-of-the-art. Both of these systems were significantly lighter than the dual TEE system.

Extension and Retraction Mechanisms

Various methods for extension and retraction were considered. These included:

- Screw jack and motor spring
- Direct motor springs
- Pneumatic cylinders

- Torsion springs at hinge joints
- Motor springs with pulley and cable or chain and sprockets
- Direct motor drive system
- Combinations of the above

Preliminary investigations indicated that the lightest approach for the folding arm system (because of the large torque loads existing at the junction of the folding arm subassembly and base structure) was obtained by using a direct motor drive system as described in Section 2.3.

Release System

The launch lock and associated release mechanisms are vital parts of the system. Failure of this subsystem to properly operate results in catastrophic failure of the mission. Various methods of restraining the spreader bar and releasing it upon command were studied. These included clamping tool mechanisms, cable "Cinch-Up" mechanisms, spring loaded latches with cables, and electrical devices such as solenoids and pyrotechnic activated devices (cable cutters, pin pullers, etc.).

Selection of the release mechanism is dependent upon the final design configuration to a large extent. Based upon lightweight, proven reliability, and simplicity, the pyrotechnic actuated explosive bolt system was selected for releasing the spreader bar. Relatching capability is not required upon subsequent retraction cycles since the structural design is capable of withstanding anticipated loads from spacecraft maneuvers with the folding arm system in the retracted position.

Deployment Rate Dampers

Various methods of controlling the rate of deployment and retraction were investigated. The design selected for the drive train operates in such a manner that a deployment/retraction damping system is not required.

Folding Arm Joint Lock System

Methods of locking the folding arm joints included positive mechanical locks, increased cable tension after joint is fully extended, fluid actuated cylinder locks, and motor driven locks. Assessment of the merits and weights of these various systems led to the selection of the cable tension locking system described in Section 2.3.

Deployed Substrate Tensioning Devices

The minimum natural frequency of the deployed array is dependent upon the tension induced and maintained in the array panel. It is desirable that the tensioning loads be applied to the panel at the end of the deployment cycle rather than existing at its full value throughout the full deployment cycle. This approach imposes a minimum loading upon the drive system and minimizes the power requirements for deployment. Various means of obtaining such tension were postulated including direct drive motors, torsion springs, and negator springs. For each of these candidate systems, various locations of the tensioning device within the system were considered. The final design employs a torsion spring located on the drive shaft between the electric motor and the storage drum driven shaft. One end of the torsion spring is retained by a bracket mounted to the base of the array. The other end of the spring is coupled to the drive shaft through a series of limit stop washers which, through sequential engagement, delay engagement of the spring until the last one half revolution of the storage drum upon extension.

Throughout the study and the detailed design of the flight article and the functional model, a continuing effort existed to optimize the design from the standpoints of fabrication simplicity, operational reliability, and functional characteristics.

2.4.2 Electrical Studies

The electrical system design studies are based upon the ground rules given in Sections 2.1 and 2.2 and in Reference 1. The details of this study are contained in Reference 3. The following paragraphs briefly summarize the efforts so reported.

Solar Cell Efficiency

The cell to be supplied is a 2 x 2 cm, 10 ohm cm, silicone solar cell of .008 inch thickness having an active area of 3.9 cm squared. At the peak power point, this cell is to produce a maximum of 49.5 milliwatts under bare cell conditions at 55°C cell temperature. This is equivalent to a nominal cell efficiency of 10.78% at 28°C. The EI characteristic curve for the above cell was derived from a curve for a 10.13% efficient cell at 28°C and is presented in Figure 2.4.2-1. Primary power losses are classified as

- Cell mismatch 1%
- Coverglass and adhesive 4%
- String interconnections 1%

Total 6%

These losses result in reduction of the maximum power point of the cell to 46.57 milliwatts as indicated in Figure 2.4.2-1. The associated voltage and current are also given.

Effect of Array Damping Materials On Cell Output

To protect the solar cells with the array in the launch configuration (rolled up), a layer of low density polyurethane foam is placed between adjacent layers of the array. The foam is attached to the back of the substrate and results in an increase in cell temperature and consequently a degradation of cell output. For a foam layer .032 inches thick and covering the total rear surface of the module, a 5°C temperature increase is experienced which results in a degradation of cell output of 3.3%. However for the flight design, approximately 75% of the rear surface of the module is exposed. The net effect of partially covering the rear surface is to cause a degradation of cell output of 0.3%.

Other factors contributing to reduced array power output are listed below:

Solar Cell Module Design

An integrated design effort was conducted in selecting the final module design. Factors considered were:

- Array panel aspect ratio
- System structural considerations
- Handling characteristics of the module
- Fabrication feasibility
- Power conditioning equipment capabilities
- Mission requirements (to Mars and to Venus)

The selected design is presented in Figure 2.4.2-2. A detailed discussion of the trade studies conducted in each of these areas is contained in Reference 3.

Parametric studies were conducted to determine the effect of power losses in the power collection harness upon the power to weight ratio of the total system. The results of this study are presented in Figure 2.4.2-3. For two buss materials, copper and aluminum, and 2 buss operating voltages 78 volts and 47 volts. The data was generated by considering that an increase in buss bar cross section (increased system weight) results in a decreased power loss. The weight of the power collection harness insulation for the selected design is accounted for and has a significant effect upon the results.

A study was made of the effect of array panel aspect ratio upon power to weight ratio of the total system. For higher aspect ratio panels, the power collection harness must extend a greater distance from the spacecraft and hence weighs more; on the other hand, for very low aspect ratios panels the transverse harnesses required on the panel to bring all power to a central slip ring causes increased weight of the total system. The results of this study are shown in Figure 2.4.2-4.

Inspection of the array panel indicates that some of the modules are close to the spacecraft while others are located at varying distances. Since all modules are identical in their electrical characteristics and, for sake of uniformity, the cross section of buss conductors is the same, those modules located furthest from the spacecraft experience a larger I^2R harness loss than modules nearer to

VOLTAGE-CURRENT CHARACTERISTICS

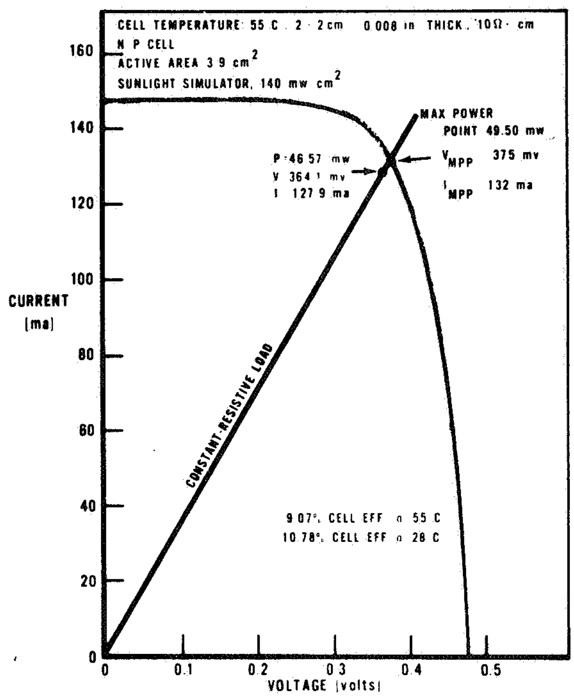


Figure 2.4.2-1

SOLAR CELL MODULE CURRENT PATHS

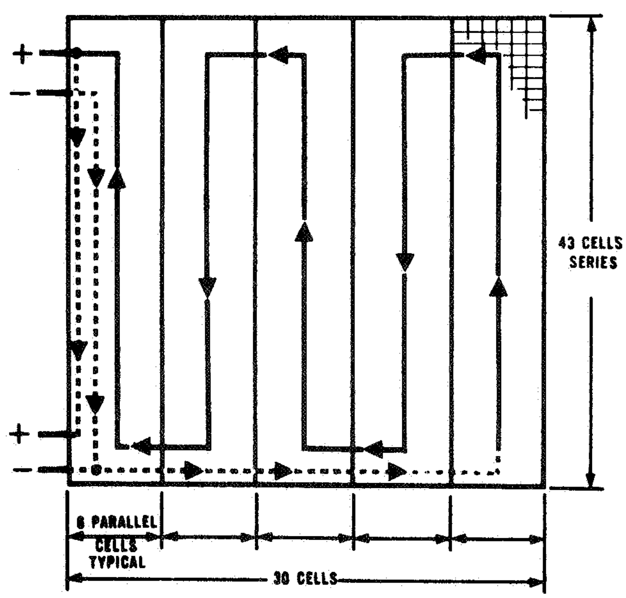


Figure 2.4.2-2

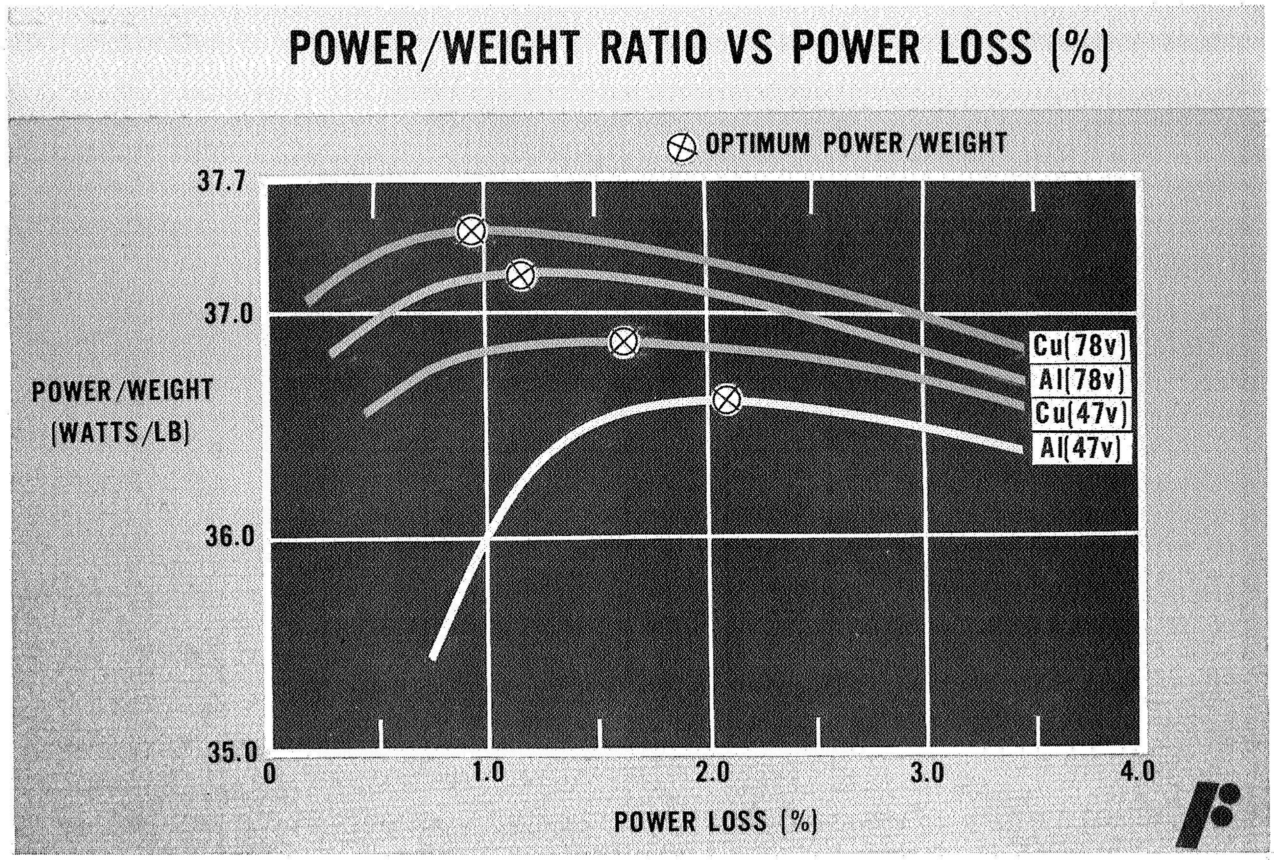


Figure 2.4.2-3

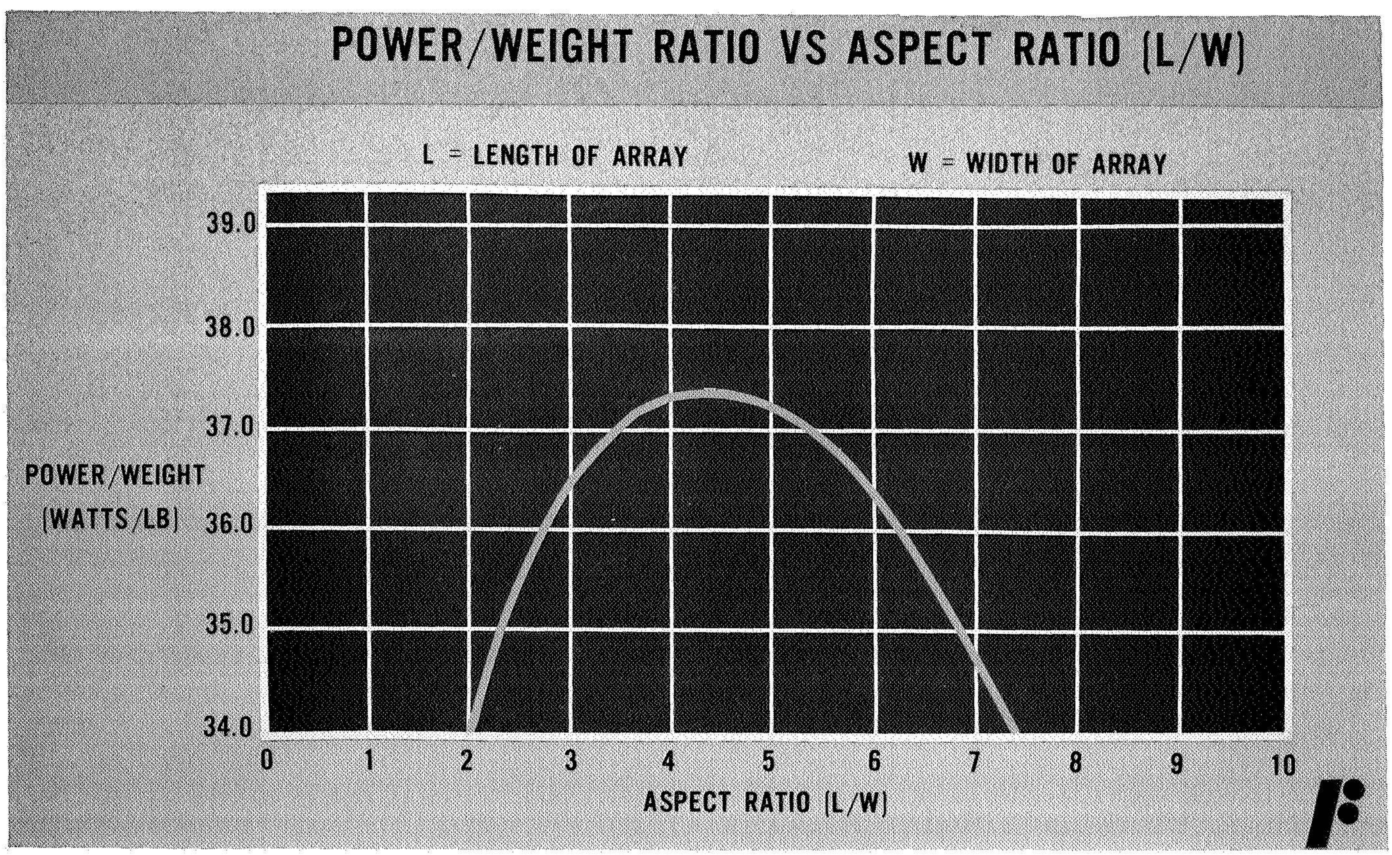


Figure 2.4.2-4

the spacecraft. This unbalance in voltage input to the common terminal at the drum is equivalent to a 0.22% loss in array power output. (Table 2.4.2-1)

Each module is connected to its power collection harness through two redundant electrical connectors, each of which uses two (2) contact pins for each circuit wire and also provides a place for a test probe to be installed for checking the module. ITT Cannon connector type MTB was selected for this application. Figure 2.4.2-5 illustrates the harness/module electrical interface schematically.

Blocking diodes will not be used in the final design. However, they were used in the preliminary calculations of the array output power.

Table 2.4.2-2 summarizes the array power calculations and identifies the various losses connected therewith.

2.4.3 Thermal Studies

The thermal studies conducted during the program investigate the thermal characteristics and responses of the array panel and supporting structure for a variety of environmental conditions which would be encountered on missions to Venus, Mars, and around Earth at both high and low orbits. For an array always oriented normal to the solar flux, the missions to Venus and Mars produce essentially steady state conditions with temperature variations dependent only upon the distance from the sun. Conversely, earth orbital missions are characterised by sharp changes in the solar flux which produce transient thermal environments and thermal shock. The most severe environment in each case was used to assess the thermal effects upon the structure and panel for various design concepts. Thus the investigation included both equalibrium temperatures and transient temperature phenomenon.

Array temperature transients associated with both Earth and Mars planet shadow were determined together with the incident solar flux with a number of effects taken into account. Thermal masses of .03 and .075 BTU/^{o}F ft.^{2} were considered as two reasonable extremes for the array panel. Temperature decay of the array in the planet shadow with penumbra effects included was computed as a function of time and incident IR radiated flux. Transient temperature behavior

TABLE 2.4.2-1

ARRAY POWER LOSSES

Power Loss Due To .032 inch Polyurethane Foam Backing:	
(Partial Coverage, .187" Strips):	0.3%
Heat Emitted By Folding Arm:	1.0%
Module/Array Harness Connectors:	0.002%
Slip Rings:	0.113%
Harness:	0.98%
Blocking Diodes:	1.03%
Bus Loading:	0.22%
Cell Mismatch:	1.00%
Coverglass and Adhesive:	4.00%
Cell String Interconnectors:	1.00%
TOTAL POWER LOSSES:	9.65%

TABLE 2.4.2-2

Array Power Calculation Summary

Cell
2 x 2 cm x .008 in. thk.
N/P cell at 55°C
Active Area = 3.9 cm^2
Illum. - 140 mw/cm^2

Primary Power Losses
Cell Mismatch - 1.0%
Cover glass & Adhesive - 4.0%
String Interconnections - 1.0%

Other System & Configuration Power Losses
Foam Backing - 0.3%
Beam Reflection - 1.0%
Module Conn. -0.002%
Slip Rings - 0.113%
Harness - 0.98%
Blocking Diodes - 1.03%
Bus Loading - 0.22%

Configuration	Bare Cell			Cell With Primary Losses			Array Output Characteristics		
	Voltage (volts)	Current (amps)	Power (watts)	Voltage (volts)	Current (amps)	Power (watts)	Voltage (volts)	Current (amps)	Power (watts)
Cell @ 55°C, IAU	.375	.132	.0495						
Module 1290 cells, in parallel, 215 in series	80.625	.792	63.855	78.28 97.1%	0.7674 96.9%	60.0732 94.0%			
Array 48 parallel Modules	80.625	38.016	3065.0				74.9834 93.0%	36.835 96.8%	2762.0 90.0%

MODULE/HARNESS ELECTRICAL INTERFACE SCHEMATIC

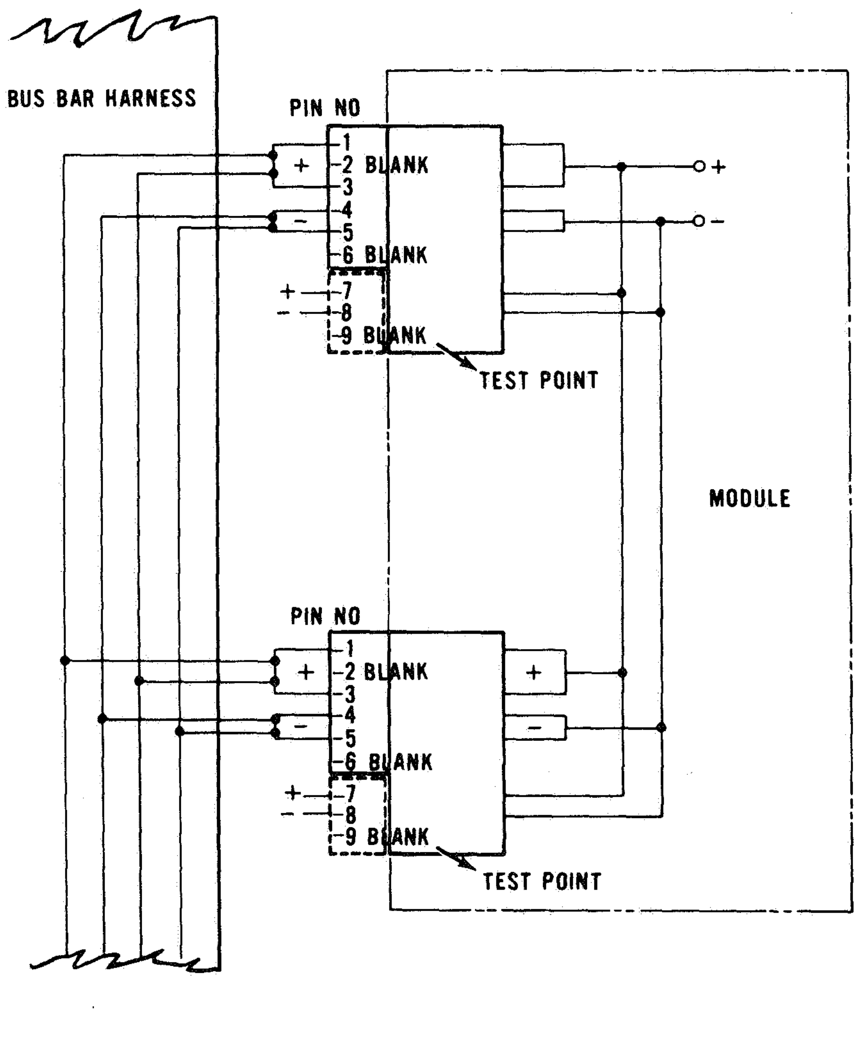


Figure 2.4.2-5

of the array upon emerging from earth shadow was similarly determined.

The steady state temperature of the array in the Earth's shadow as a function of array attitude and altitude with Earth emission as the only radiative input was computed for various angles between the array and the local vertical.

One of the most significant factors affecting the selection of the final array panel/supporting arm structure configuration is that of the mutual interaction of radiative fluxes between these components. Two radically different environments were examined: first, with a longitudinal gap in the array substrate sheet directly above the entire arm length, and second, with a continuous substrate protecting the folding arm beam from the direct flux of the sun. A thermal model of the arm and array was developed as illustrated in Figure 2.4.3-1. The array components considered in thermal analysis are illustrated in Figure 2.4.3-2. Array temperature for each condition were computed as a function of distance from the center line of the beam. Thermal gradients throughout the circumference of the folding arm element were also computed for both conditions. Various surface absorptivities and emissivities were considered so that the effects of various thermal coatings upon array temperatures and beam temperature gradients could be assessed. Figures 2.4.3-3 and 2.4.3-4 present typical results of this study. The temperature distribution of the array in the vicinity of the arm is shown in Figure 2.4.3-5.

As a result of these studies and as shown in Figure 2.4.3-3, the circumferential temperature gradients in the arm element are unacceptably high when the arm is exposed to the direct rays of the sun, being on the order of 200 to 220°F. Conversely, for the condition of the arm being subjected only to reradiated flux from the array, circumferential temperature gradients are 15 to 20°F. For these reasons the final configuration embodies an array panel which protects the supporting arm structure from the direct rays of the sun.

The results of these studies are presented in detail in Reference 3 by means of graphs and descriptive text which defines the limits of the various parameters and the assumptions used in the analysis.

THERMAL MODEL OF ARRAY AND ARM

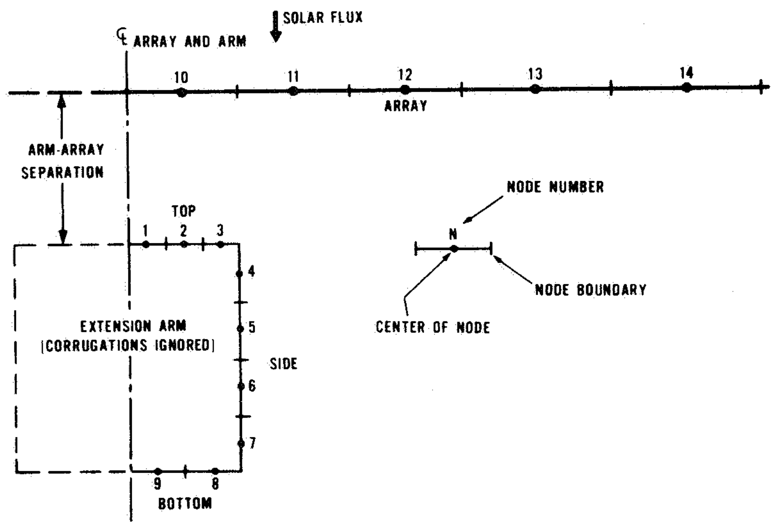


Figure 2.4.3-1

ARRAY COMPONENTS CONSIDERED IN THERMAL ANALYSIS

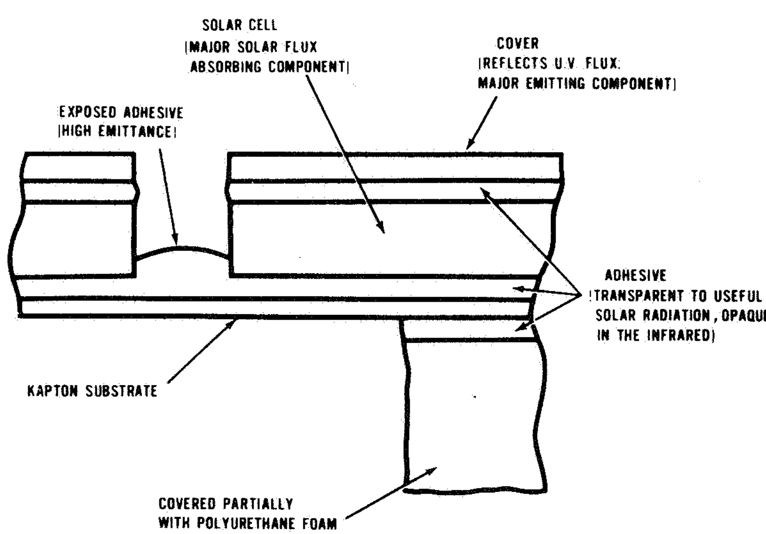


Figure 2.4.3-2

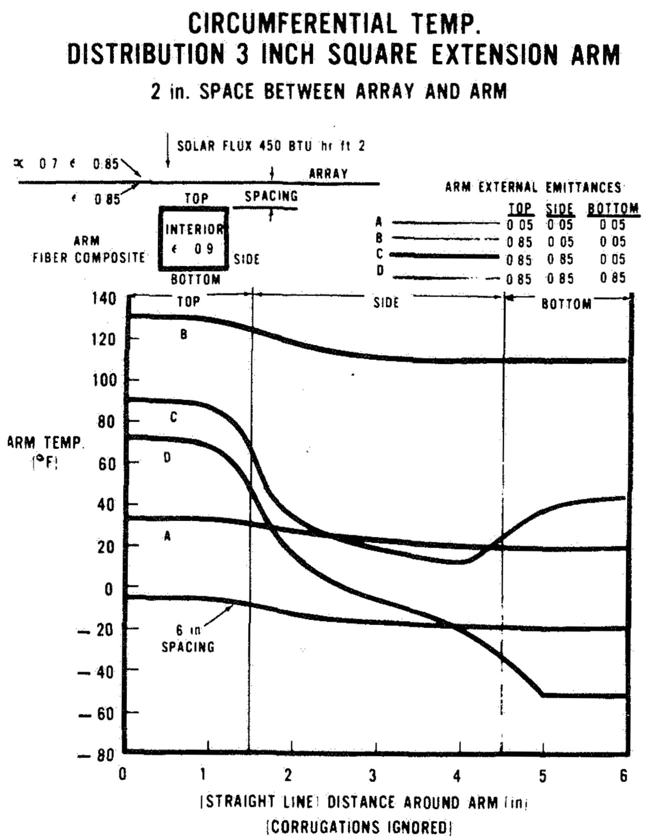


Figure 2.4.3-3

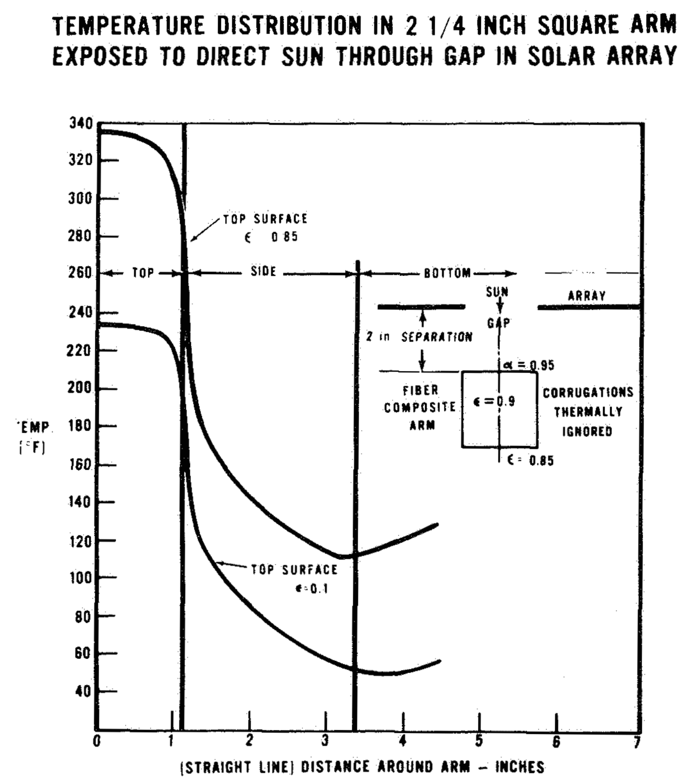


Figure 2.4.3-4

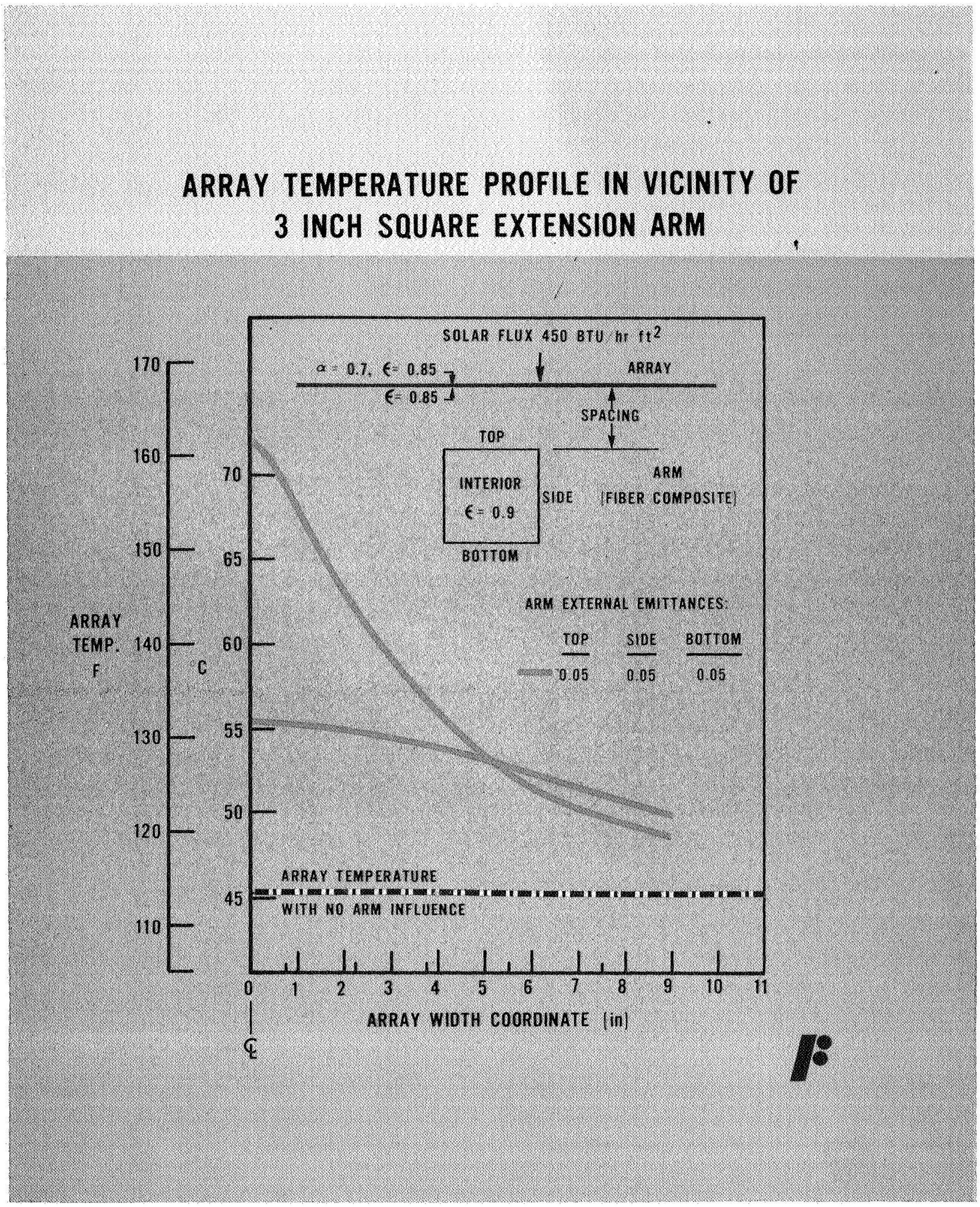

ARRAY TEMPERATURE PROFILE IN VICINITY OF
3 INCH SQUARE EXTENSION ARM
SOLAR FLUX 450 BTU/hr ft^2
α = 0.7, ϵ = 0.85
ϵ = 0.85
ARRAY
SPACING
TOP
INTERIOR
ϵ = 0.9
SIDE
BOTTOM
ARM
(FIBER COMPOSITE)
ARM EXTERNAL EMITTANCES:
TOP
SIDE
BOTTOM
0.05
0.05
0.05
ARRAY TEMP.
F
C
ARRAY TEMPERATURE
WITH NO ARM INFLUENCE
ARRAY WIDTH COORDINATE (in)
170
160
150
140
130
120
110
70
65
60
55
50
45
0
1
2
3
4
5
6
7
8
9
10
11

Figure 2.4.3-5

2.4.4 Materials Studies

The selection of the best material for a specific application in any design is of vital concern since the successful performance of the unit is largely dependent upon the capability of the constituent materials to respond in a predictable manner to the operational environments. This problem is of special concern for the roll-up solar array design study since, combined with performance, there is the pressing need to minimize weight. Therefore, material efficiency in performing its design function must be one criterion on which the various candidate materials are evaluated.

The study requirement of using 1968 state-of-the-art technology deletes from consideration several new and promising materials and places on the designer the burden of evaluating the capability of relatively new materials to meet this test. Sound engineering judgement based on prior experience, documented test data and previous application and performance of each material must be used in approving or rejecting a material's state-of-the-art status. Where test data is not available, it has been obtained (sometimes in limited quantity) to indicate the trend of the materials performance and thus add confidence to material selection decisions. This philosophy prevails throughout the materials studies conducted on the current program.

Investigations have concentrated on assembling data on candidate materials. Materials with well documented properties, such as aluminum and steel, have received nominal effort; the less common materials, more emphasis. Particular attention was given to the environmental response of plastics, thermal coatings, and composite materials exhibiting high strength and stiffness efficiencies. Sources of data included the literature, reports of prior performance in space application, vendor contacts and in-house tests.

This section summarizes the tests conducted, the materials selected for the final design, and the reasons for the selection.

Structural Materials

Structural materials used in the design include aluminum alloys for the base of the array and various small bracketry; boron/epoxy composite materials for the folding arm tubular elements and the spreader bar; graphite/epoxy composite material for the array panel storage drum; beryllium for fittings and pulleys; Kapton H film for the panel substrate; polyurethane foam, mounted to the back of the substrate as a damper and protective blanket between layers of the panel when stored on the storage drum; and high strength steels for highly loaded gears and mechanical elements. Various adhesives, lubricants and thermal control coatings were investigated. Expanded silver mash is used for electrical interconnection of the solar cells and copper for harness buss wiring.

The primary requirement for the material used in the folding arm tubular elements is that it possess a high stiffness to weight ratio (high modulus of elasticity) since these elements are loaded primarily as beam columns. Boron and graphite filaments or fibers in an epoxy resin matrix exhibit these properties to a high degree. The boron/epoxy composite material has been under development for several years and is currently being used on a number of aerospace programs in limited quantities. The graphite/epoxy composite is quite new and, while it possess striking qualities in the direction parallel to the fiber orientation, its transverse shear properties are very low. Thus it must be used with caution and only in applications in which the internal loads are well defined. Fiber orientation must be tailored to provide strength where required. Table 2.4.4-1 lists the comparative properties of various structural materials. Specific modulus and specific strengths are defined respectively as modulus of elasticity/density and tensile strength/density. The values are relative with those materials having high values being the more efficient in the particular characteristic under consideration. Inspection of the table reveals that the efficiencies of titanium, stainless steel, aluminum and magnesium are approximately the same. Beryllium is exceptionally good in applications requiring high stiffness but its relative strength efficiency is no better than the more common metals. The composite materials are significantly better in strength efficiency with graphite composite exceeding beryllium and the boron composite significantly better than the more common metals but not as good as beryllium. The boron composite material was selected for the arm tubular elements rather than graphite composite primarily because of a matter of confidence in its performance in this application. As more

TABLE 2.4.4-1

STRUCTURAL MATERIALS COMPARATIVE PROPERTIES

	SPECIFIC MODULUS	SPECIFIC STRENGTH	DENSITY Lb./In.^{3}
Boron Filament/Epoxy Composite (2 ply - 15° Half Angle Layup)	466	154	.075
Graphite Fiber/Epoxy Composite (2 ply - 15° Half Angle Layup)	666	222	.052
Beryllium (2% BeO)	635	104	.067
Titanium (6 Al 4 V)	102	98	.160
Stainless Steel (17-7 PH)	104	85	.277
Aluminum (7075-T6)	102	75	.101
Magnesium (AZ31B)	102	61	.064

experience is gained in the use of the graphite composites, they may well prove to be the structure materials of the future for space applications.

The graphite composite material is used in the storage drum since its peculiar combinations of longitudinal and lateral strength and stiffness properties can be used to an advantage and with confidence in this application.

Beryllium

The folding arm element end fittings and cable system pulleys are fabricated from beryllium to obtain a minimum weight design.

The weight of the beryllium parts is dictated primarily by the minimum thickness which may be obtained by present fabrication techniques. Machining .125 inch thickness poses no particular problem and chemical milling will permit reduction of the thickness to .06 inches. These processes will be used in fabricating the fittings and the pulleys.

Beryllium is also selected as a "back-up" material for fabricating the folding arm tubular elements if tests of the boron/epoxy composite material tubes should prove this material to be undesirable for the application. Hot formed sheet, with corrugations, can be produced and brazed to fabricate long thin wall elements. The minimum wall thickness which may be obtained with 1968 state-of-the-art techniques is on the order of .020 inches. Therefore the use of beryllium in this application will result in a weight penalty (Reference Section 2.4.5).

Polyimide Film

Selection of Kapton H film is based upon its superior thermal and radiation resistance performance. The tendencies of thin Kapton film to tear easily at edge defects is overcome by bonding a doubler of the same material in such areas. Two mil thick Kapton material is used for the array panel module substrate. Modules are connected together by a simple lacing technique using 5 mil thick Kapton film for the lacing. Tests were conducted (Figure 2.4.4-1) to determine the feasibility of this method of mechanical attachment. For unsupported Kapton film, loads in excess of 9 pounds per inch of weight were

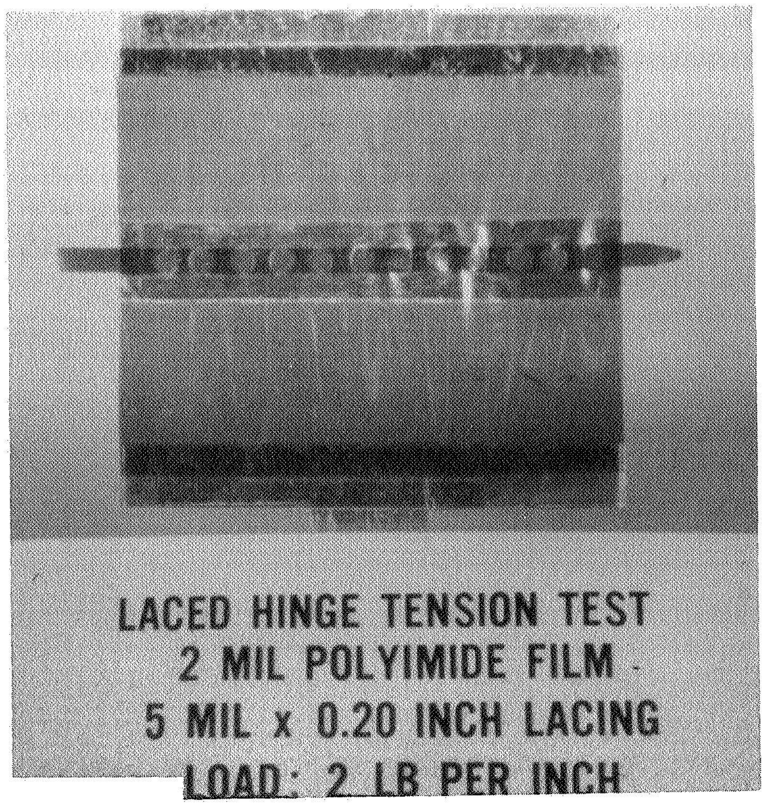


Figure 2.4.4-1

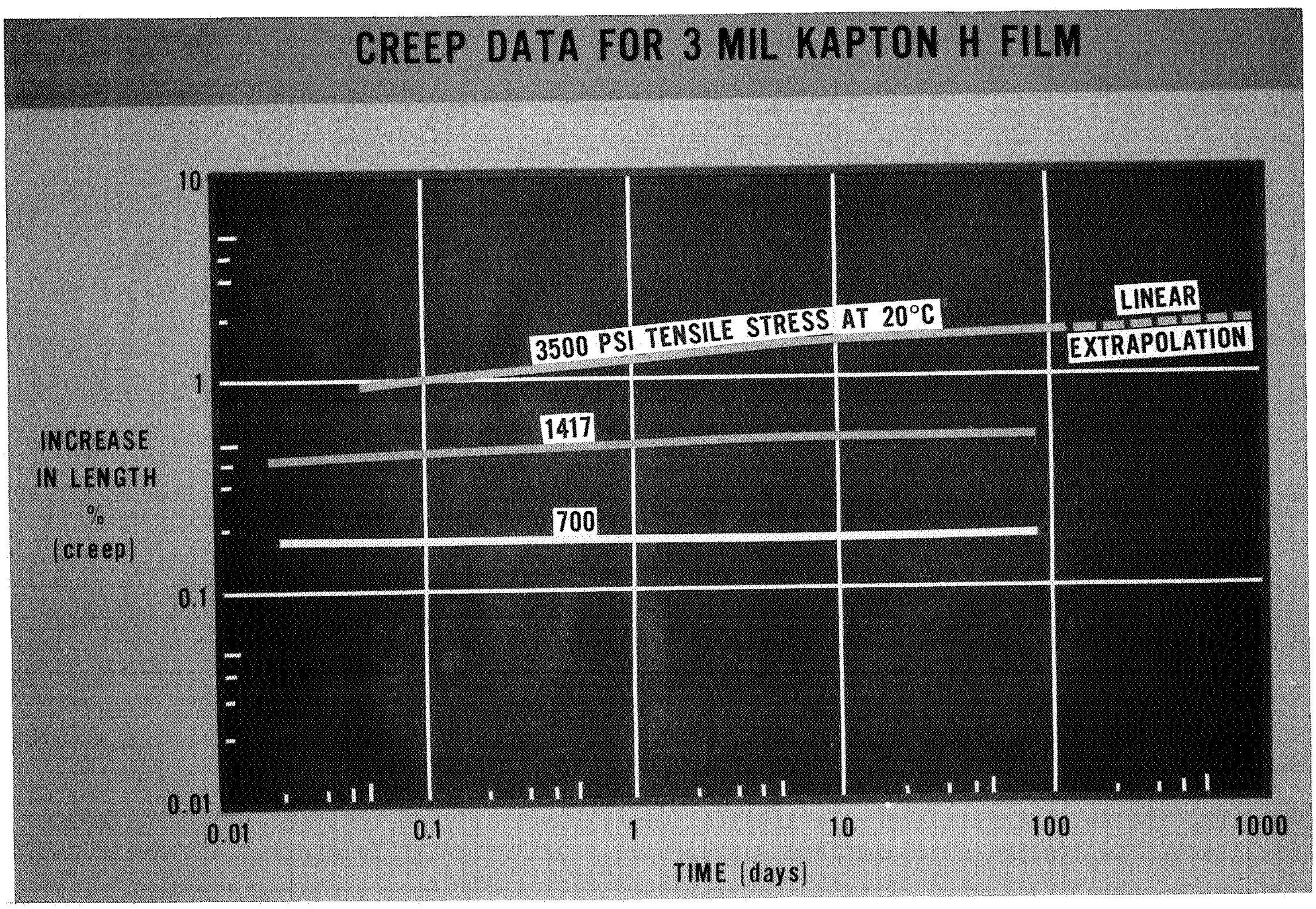


Figure 2.4.4-2

obtained without tear out; at this load the sample unlaced. Since design load is on the order of 0.1 pounds per linear inch, the method of attachment is satisfactory and provides a high margin of safety.

The final design subjects the Kapton substrate of the deployed panel to a tension load for the entire mission life time. Creep characteristics of the substrate material, thus, are of interest. Tests were conducted at room temperature on the three mil Kapton H film (Figure 2.4.4-2) at various stress levels. The design stress in the substrate is 50 psi; comparing this to the data obtained, no problem is anticipated over the range of temperatures to which the substrate will be subjected.

Adhesives

Adhesives are used in the design to bond cover glasses to cells, cells to substrate, doublers to substrate, fittings to boron/epoxy composite tubing, polyurethane foam to the substrate, and in fabricating the power collection harness.

Sylgard 182 is selected for bonding cover glasses to cells, based upon its successful prior use in similar applications. HT432 (epoxy, Bloomingdale Rubber) is selected for bonding substrate doublers and electrical connectors to the substrate. RTV108 (flexible silicone adhesive) was selected for bonding cells to substrate based upon Fairchild Hillers' experience in using this adhesive on the deployable solar array program conducted for GSFC (Contract No. NAS5-9658). The adhesive has adequate strength for this application and permits individual cell replacement without damage to the substrate because of its relatively low tensile strength.

DC281 (a pressure sensitive silicone adhesive) was selected for bonding the foam backing to the substrate. This adhesive, however, exhibits very high weight loss when subjected to thermal vacuum conditions although the reduction in strength is very small and of little consequence in this application. It is expected, but has not be proven, that preconditioning of the modules/foam backing combination will result in the material stabilizing to an acceptable level of weight loss and emission of volatile condensible materials. In the event that such is not the case, one of the flexible epoxy adhesives may be substituted for DC281 but with additional complexity of fabrication.

Lubrication

The selected design employs a number of bearings at rotating joints and in the drive train. A design requirement is that the unit must be capable of retraction and extension at any time during a mission lasting 245 days. Thus, lubrication of these bearings must be assured even after long exposure to space environmental conditions and extremes of temperature. Past experience with very highly loaded slow speed bearings exposured to hard space vacuum is limited; however, an insite into the problem may be gained through the experiences of Nimbus, OGO, Pegasus I and II, and the Mariner and Ranger Series. Based upon this experience and on the published results of tests conducted on various lubricants, lubrication for the final design will consist primarily of molybdenum sulfide burnished onto steel to obtain a very low sliding and rolling friction with break away friction decreased by a very thin film of Apiezon type grease.

Experimental Determination of the Emmittance of the Back Surface Of the Array

The emmittance of the backing surface of the array was determined experimentally to confirm the values used in the thermal analysis. The effective emittance was determined to be 0.85 and thus is in close agreement with the assumed value used in the thermal analysis.

Solar Cell Structural Integrity Tests

A roll up flexible substrate solar cell array concept is based upon the premise that rigid silicone cells, mounted on the flexible substrate, can be stored on a drum or roller during launch and subsequently deployed. A series of tests were conducted to determine the relationship which exists between drum diameter, substrate tension with a portion of the substrate/cell stack combination wrapped on the drum, and ultimately, the cell failure load when subjected to this condition. This work was a continuation of similar investigations conducted by Fairchild Hiller Corporation for the Goddard Space Flight Center under Contract No.

NAS-5-9658. Equipment developed on this prior investigation was used in conducting the current tests. Figure 2.4.4-3 shows the test set-up. The results of these tests combined with results of the prior tests are illustrated in Figure 2.4.4-4. Inspection of the graph indicates that the design point of 0.1 pounds per inch is well below the critical values of loading for the cell/coverglass combination used in the design.

2.4.5 Structural Analysis and Weight Studies

The analytical criteria for the design is specified in Reference 1 and summarized in Table 2.4.5-1. The requirement that the minimum resonant frequency of the array exceed 0.04 Hz. dominated the design investigation from their inception. The nomogram shown in Figure 2.4.5-1 was developed to aid in investigating the relationship between the various parameters effecting the natural frequency of the array panel. Inspection of this graph reveals that, for practical values of array aspect ratios and substrate density (pounds/sq. ft.) and if the array tension is maintained at or in excess of 5 pounds, no problem will be encountered. Subsequented investigations of the natural frequency of the extended folding arm system have shown that the structural members exceed this criteria by a substantial margin (Reference Table 1.2-2).

The structural analysis and weight studies are divided into two general categories: investigation of system weight as a function of the system parameters, and stress analysis of the final design.

Parametric Investigations

Investigations of the folding arm weight, TEE device weights, and Hingelock tube concept, were conducted for various candidate structural materials, array aspect ratio, and array panel tension. Array tension was varied between 5 and 20 pounds, array width between 6 and 12 feet. Typical results of these investigations are presented in Figure 2.4.5-2. A detailed analysis and design of the structural elements of each concept was conducted and the design optimized for minimum weight while meeting the design criteria. Figure 2.4.5-3 illustrates the typical loading analysis of the folding arm system. The variation in folding arm weight as a function of length and array tension is illustrated in Figure 2.4.5-4

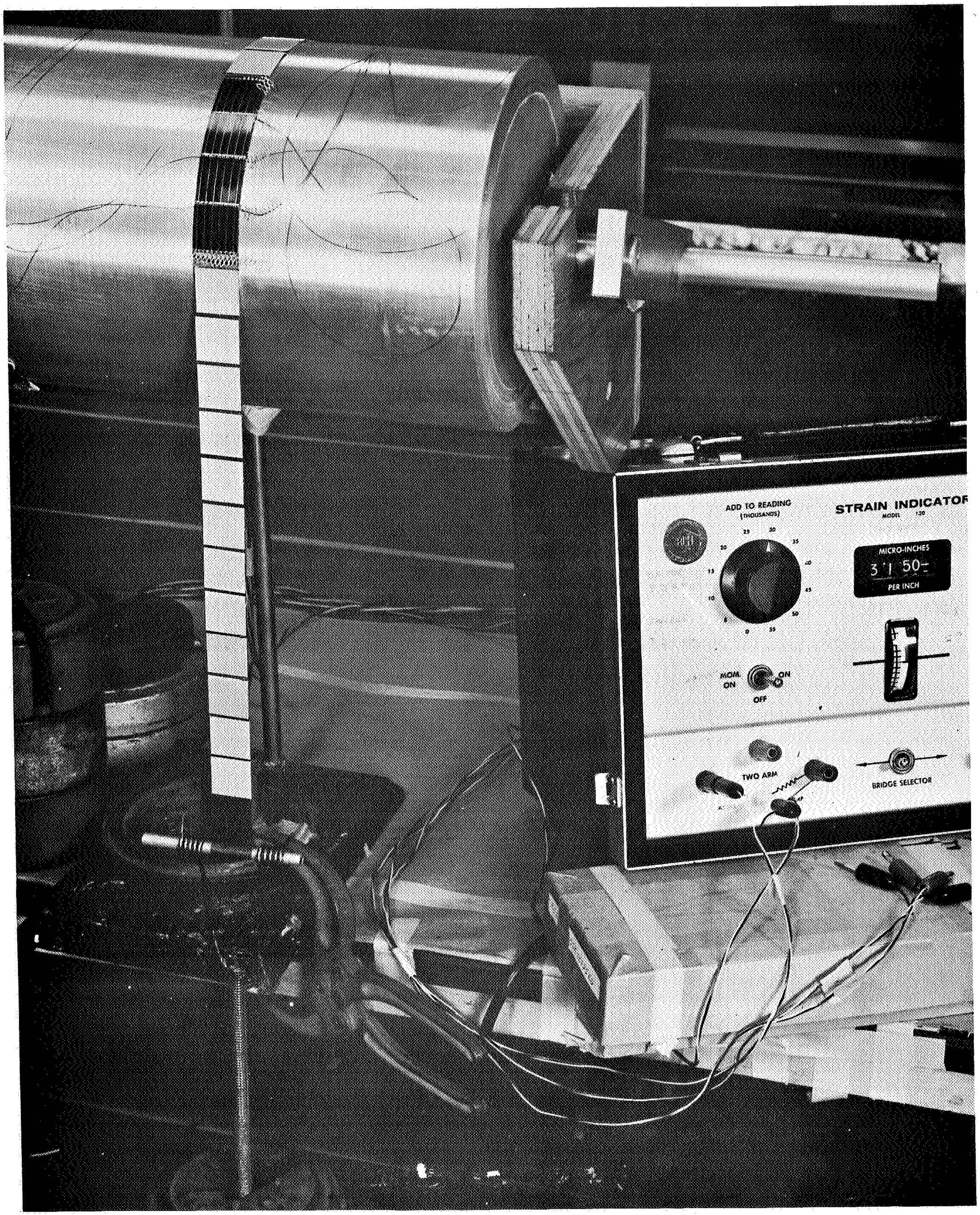

ADD TO READING
(THOUSANDS)
STRAIN INDICATOR
MICRO-INCHES
PER INCH
MOM. ON
ON
OFF
TWO ARM
BRIDGE SELECTOR

Figure 2.4.4-3

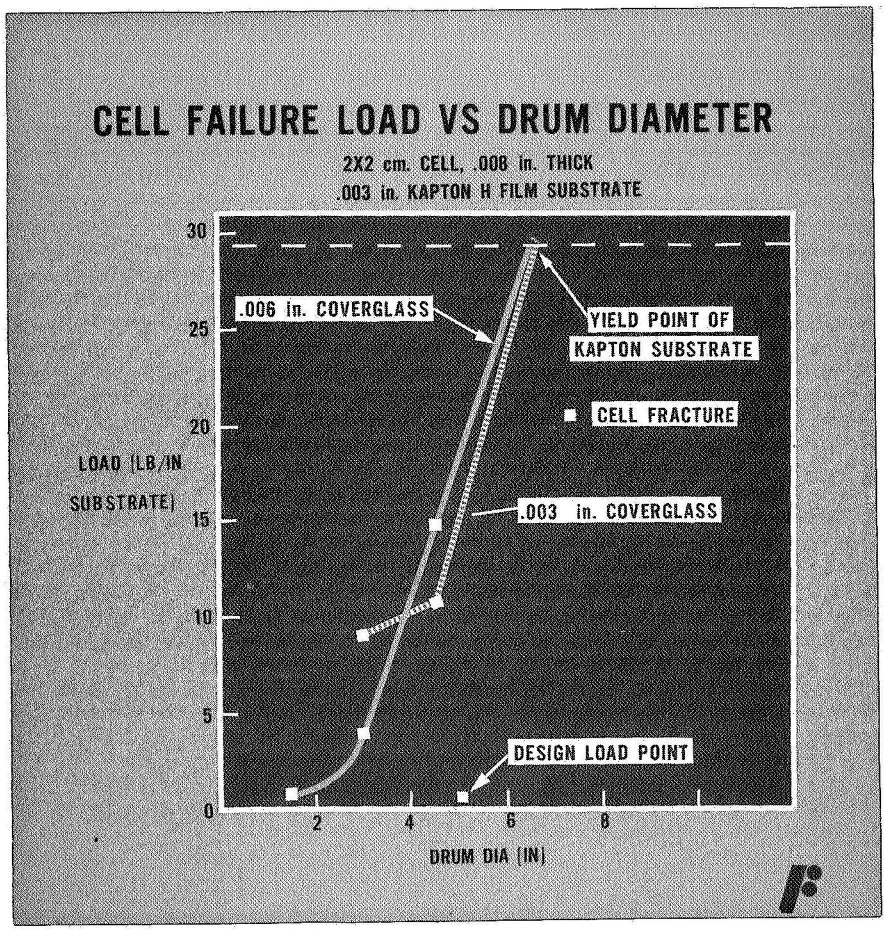

CELL FAILURE LOAD VS DRUM DIAMETER
2X2 cm. CELL, .008 in. THICK
.003 in. KAPTON H FILM SUBSTRATE
30
25
20
15
10
5
0
LOAD (LB/IN SUBSTRATE)
.006 in. COVERGLASS
YIELD POINT OF KAPTON SUBSTRATE
CELL FRACTURE
.003 in. COVERGLASS
DESIGN LOAD POINT
2
4
6
8
DRUM DIA (IN)

Figure 2.4.4-4

TABLE 2.4.5-1

ANALYTICAL CRITERIA

LAUNCH

- ACCELERATION = +13g or -4g longitudinal
  -6g lateral
- VIBRATION:
  SINUSOIDAL: 0 to 200 Hz with 2.0 octaves/min. sweep @ 4.0g, 0 to peak
  RANDOM: 3.0 min. @ $0.1g^2$/Hz - 200 to 600 Hz
  6.0 db/octave below 200 Hz & above 600 Hz
- ACOUSTIC: 200 to 1000 Hz @ 125 to 138 db/ 1/3 octave bands

SPATIAL

- ACCELERATION: sq. wave pulse, 13.0 sec. to 5.6 min. duration, max. amplitude 2.0×10^{-5} rad./sec.^{2}
- THERMAL GRADIENTS: 260 mw/cm^2 intensity
- RIGIDITY: ± 10° normal to sun
- RESONANT FREQUENCY: 0.04 Hz min.

DESIGN FACTORS

- ULTIMATE LOAD = 1.25 x limit load
- CABLE ASSEMBLY (Design Load) = 1.5 x limit load
- FITTING FACTOR = 1.15

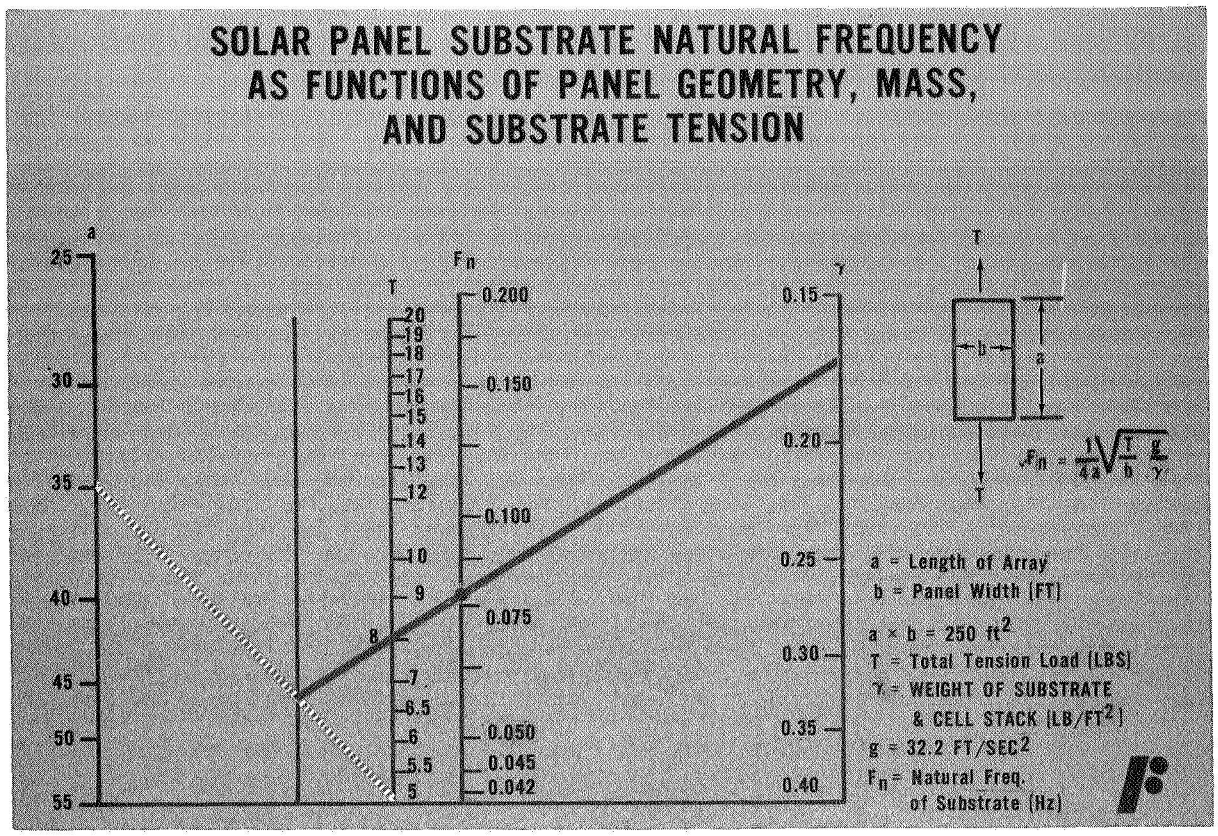


Figure 2.4.5-1

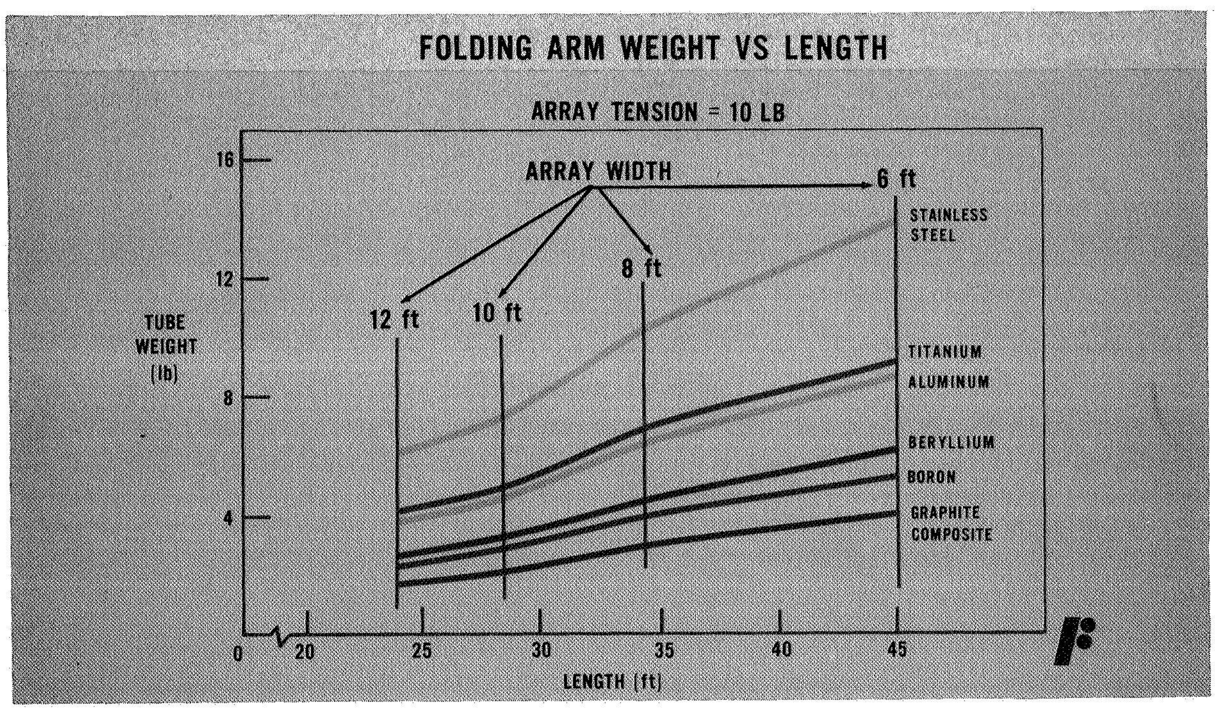


Figure 2.4.5-2

FOLDING 5 SEGMENT ARM - LOAD ANALYSIS

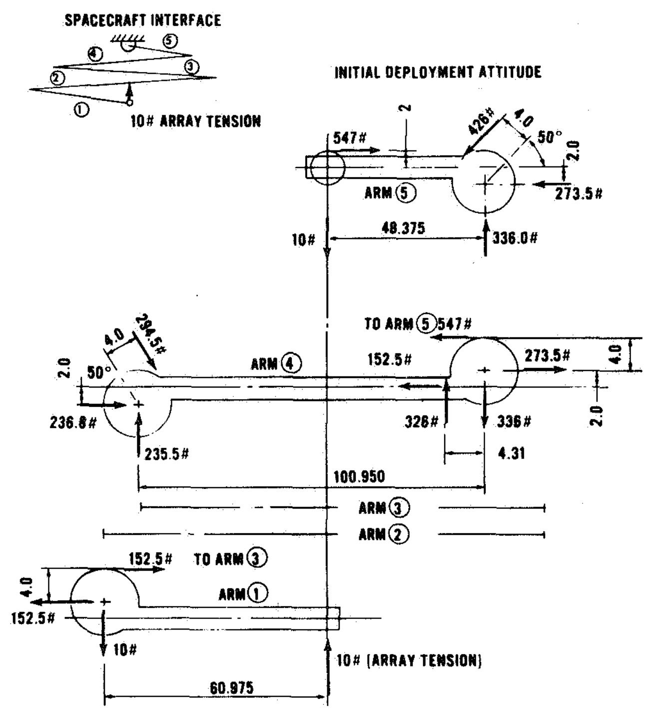


Figure 2.4.5-3

FOLDING ARM WEIGHT VS LENGTH

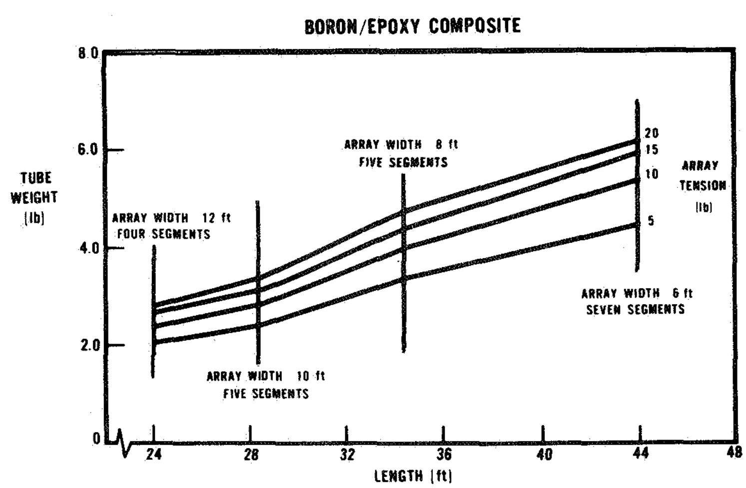


Figure 2.4.5-4

for the boron/epoxy composite material. Figure 2.4.5-2 graphically illustrates the advantages of the composite materials over the beryllium and more conventional metallic materials. The boron/epoxy composite material arm was selected for the final design for the reasons given in the materials studies, Section 2.4.4. A typical summary of the folding arm substrate system weight for the boron/epoxy arms is given in Table 2.4.5-2. Inspection of this table would indicate that the wider the array, the lower the overall weight. This is true for the subsystem as shown; however, there are offsetting and compensating weight increases as array width is increased as can be seen in Figure 2.4.5-5. This figure also illustrates the marked advantage the graphite/epoxy composite material enjoys over the other materials considered.

The results of the subsystem parametric studies are combined to obtain a total system weight as a function of array width and panel tensions and are presented in graph form. (Figure 2.4.5-6) A typical break down of these subsystem weights is given in Table 2.4.5-3. It is interesting to note that the minimum weight for the total system occurs for array widths on the order of 8 to 9 feet which corresponds to an aspect ratio for the array panel of approximately four (4). This aspect ratio has appeared as the optimum value in many of the studies conducted by the various disciplines and is, indeed, the one selected for the final design.

Similar curves were generated during the study for the dual TEE support structure concept and a single Hingelock tube panel supporting structure concept. The results of these studies are presented in detail in Reference 3.

Tables 2.4.5-4 and 2.4.5-5 summarize the array panel module weight and total system weight for the final design.

Detailed Design

The dimensions and shape of the corrugated tube used in the folding arm design were established by several factors. As shown in Figure 2.4.5-7, the tube is fabricated from two layers of boron filament, each approximately 0.0055 inches thick, layed up at 15^{o} half angle to the center line of the tube.

TABLE 2.4.5-2

FOLDING ARM SUB-SYSTEM WEIGHT
BORON/EPOXY COMPOSITE ARMS (TYPICAL SUMMARY)

ITEM	10 Pound Array Tension		
	Array Width (ft)		
	6	8	10
Internal Control System			
Hinge Pin	0.09	0.06	0.06
Cable	1.86	1.11	0.82
Cable Fittings	1.87	1.01	1.01
Cable Drum	1.17	0.75	0.55
Drum Shaft	1.29	0.71	0.55
Gear-Planetary	1.54	0.87	0.68
Gear-Fixed	4.81	2.53	2.02
Total Internal Control System	12.63	7.04	5.69
Corrugated Tubes	5.34	4.00	3.26
End Fittings	1.71	1.27	1.13
TOTAL SUB-SYSTEM	19.68	12.31	10.08

TABLE 2.4.5-3
* STRUCTURAL SYSTEM WEIGHT SUMMARY TABLE

BORON/EPOXY ARM SYSTEM - 10# ARRAY TENSION

Weights Shown Do Not Include Drive Motor,
Gear Train and Solar Array.

ITEMS	Array Width (ft)		
	6	8	10
Arm Sub-System	19.68	12.31	10.08
Spreader Bar (Boron/Epoxy)	0.80	1.02	1.24
Storage Drum (Graphite/Epoxy)	1.00	1.80	2.60
Support Structure (Aluminum)	6.00	6.00	12.50
	27.48	21.13	26.42

* Weights Shown Do Not Include Drive Motor, Gear Train & Solar Array.

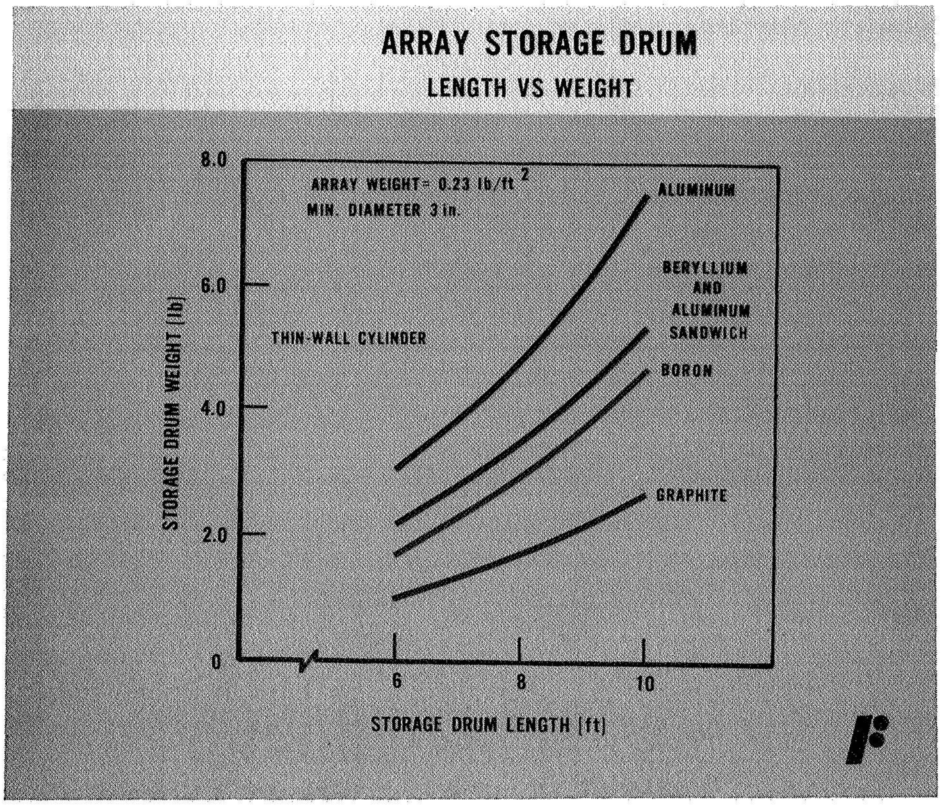


Figure 2.4.5-5

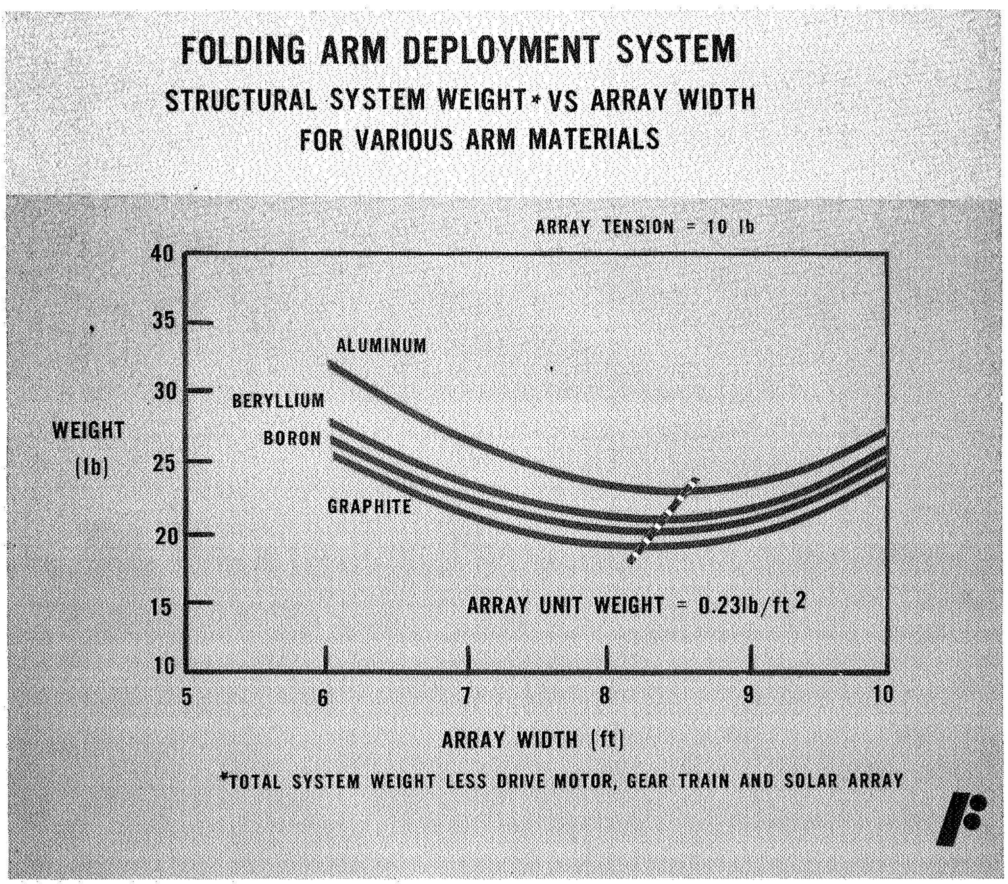


Figure 2.4.5-6

TABLE 2.4.5-4

SOLAR CELL STACK WEIGHT (lb)

COMPONENT	WT. lb/Module	WT. lb/ft^2
Cover Glass (0.003 in. Thick)	.183	.0318
Cover Glass Adhesive (Sylgard 182)	.028	.0049
Solar Cell (17 gm./100)	.482	.0837
Cell Interconnector & Solder	.051	.0089
Cell Adhesive (RTV-108)	.048	.0083
Substrate (0.002 Kapton "H" Film)	.092	.0159
Foam Adhesive	.004	.0007
Foam (2 lb/ft^3 Polyurethane)	.017	.0029
SUB TOTAL	.905	.1571
Hinge	.001	.0002
Bus Cable	.005	.0008
Elec. Cable to Module Attachment	.001	.0002
Connector (2/Module)	.001	.0002
Lateral Stiffener (5/Module)	.042	.0072
SUB TOTAL	.955	.1657
6% GROWTH WT.	.057	.0099
DESIGN TOTAL	1.012	.1756

TABLE 2.4.5-5

WEIGHT SUMMARY (lb)

	Folding Arm	TEE	Hinge-lock Tube
1 Mechanism & Supporting Structure	-	24.03	12.27
2 Folding Arms & Cabling System	12.49	-	-
3 Extendable Elements	-	9.28	4.54
4 Drive Motors & System Elements	7.52	2.13	1.46
5 Spreader Bar	1.40	1.21	1.32
6 Storage Drum	1.90	1.90	1.90
7 Storage Drum Brackets	4.71	2.02	3.11
8 Array Panel & Wiring	52.04	52.04	52.04
	80.06	92.46	76.64

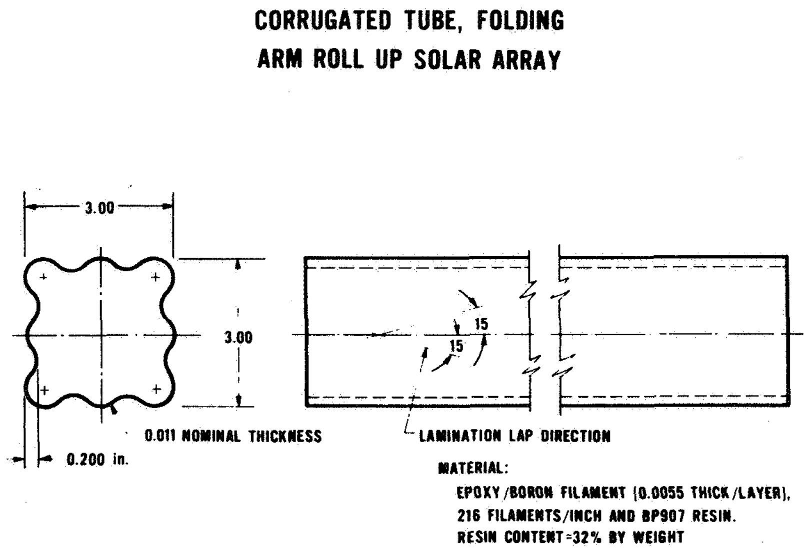


Figure 2.4.5-7

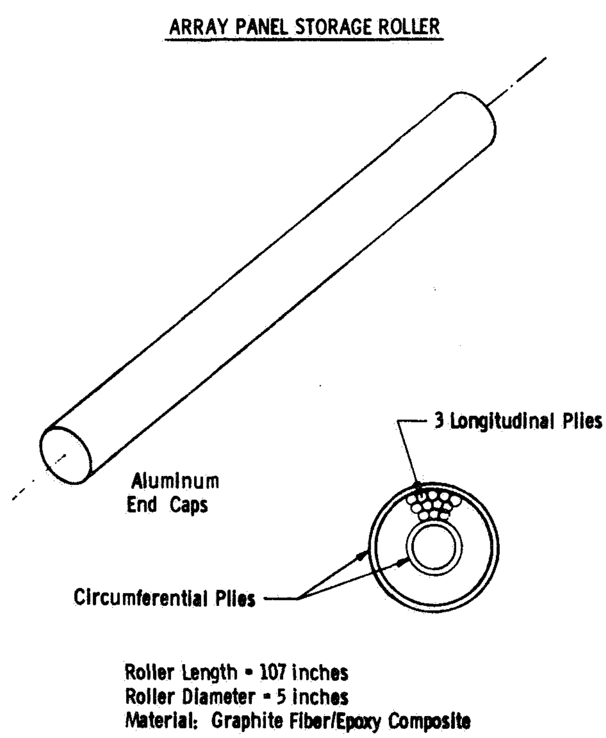


Figure 2.4.5-8

This configuration was selected to give the optimum strength of the tube for the loads it must carry. The tube is corrugated to provide stiffness against local buckling of the sidewalls. Overall dimensions of the tube are established to provide necessary bending strength for the tube when acting as a beam column.

The array panel storage roller is composed of 5 layers of graphite fiber/epoxy composite as illustrated in Figure 2.4.5-8. The inner and outer circumferential plies are so oriented to carry hoop bending loads induced by the panel during the launch environment. The three longitudinal plies located between the circumferential plies, act as a spacer so that the wall of the tube is essentially of sandwich panel construction. The three longitudinal plies also provide the necessary strength to react the beam bending loads induced in the tube.

The final design configuration was analyzed to the criteria defined at the beginning of the section. Table 2.4.5-6 summarizes the margins of safety of the various components.

2.4.6 Reliability and Failure Analysis

A reliability analysis was conducted for each of three array conceptual systems. Figure 2.4.6-1 is a functional diagram used in the reliability analysis of the folding arm mechanism. Two candidate configurations are considered: the first uses a single torquing motor for driving both the folding arm mechanism and the array roller during retraction, the second uses separate torque motors for the arms and the array panel roller. Reliability of the two systems is .9998 and .9997 respectively. Similar analysis were conducted for the dual TEE concepts, and the single tube Hingelock concept. Reliability of the Hingelock is .9999 and for the dual TEE is .9998.

A failure effects analysis of the selected folding arm design was performed. Bearing failure is a prime potential composite of system failure. In 15 of 21 cases, where no compensating provision is made, the failure would occur in a bearing. Increased reliability of the system may be obtained by installing redundant bearings, that is, placing of the outer races of a shaft bearing within a larger bearing. This approach has been used on spacecraft but imposes a weight penalty.

TABLE 2.4.5-6

SUMMARY MARGINS OF SAFETY

	Item	Material	Type of Loading	Critical Condition	M.S.
1.	Storage Drum	Graphite/ Epoxy	Beam Bending	Booster Flight	+0.08
2.	Folding Arm	Boron/Epoxy	Beam Column	Array Deploy	+1.02
3.	Cable	Stainless Steel	Tension	Array Deploy	+0.12*
4.	Pulley Web	Beryllium	Compression Buckling	Array Deploy	Large
5.	Pulley Lock Plate	7075-T6 Bare Sheet	Bending	Array Deploy	+0.33
6.	Pulley Shaft	2024-T4 Bar	Bending	Array Deploy	+2.51
7.	Idler Bracket Shaft	7075-T6 Tube	Bending	Array Deploy	+0.69
8.	Cable End Fittings	Corros. Resis-tant Steel	Tension	Array Deploy	+0.12*
9.	Gear Train	17-4PH Stain-less Steel	Bending	Array Deploy	+0.175
10.	Folding Arm End Fitting	Beryllium Bar	Bending	Booster Flight	+0.178
11.	Spreader Bar	Boron/Epoxy	Bending	Booster Flight	+4.90
12.	End Plate, Lower Web	2024-T42 Bare Sheet	Shear Buckling	Booster Flight	+0.013
13.	End Plate, Upper Web	2024-T42 Bare Sheet	Shear Buckling	Booster Flight	+0.054
14.	End Plate, Center Web	2024-T42 Bare Sheet	Beam Column	Booster Flight	+0.00
15.	End Plate, Side Brace	2024-T42 Tube	Column	Booster Flight	+0.017

* Ultimate Factor Of Safety = 1.50

FOLDING ARM MECHANISM FUNCTIONAL BLOCK DIAGRAM

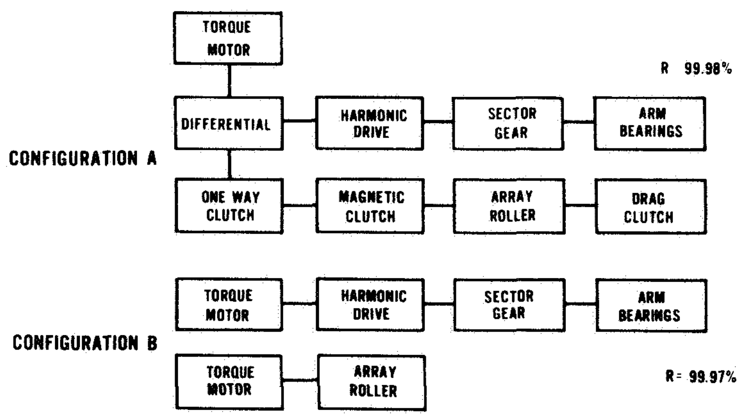


Figure 2.4.6-1

2.5 FULL SCALE FUNCTIONAL MECHANICAL MODEL

2.5.1 Model Description

The full scale model, fabricated to prove the feasibility of the selected design concept for deployment and retraction of a roll-up solar array, is identical to the flight article in its basic lines and dimensions but substitutes commercial parts wherever possible for special, lightweight design components and also substitutes aluminum alloy for the boron/epoxy composite material, folding arm tube elements and beryllium parts. The launch-lock release mechanism employs a solenoid activated release rather than a pyrotechnic latch release as designed for the flight article. A five inch diameter aluminum tube is used in lieu of the graphite/epoxy composite material for the storage drum. The flexible solar-array panel, which in the flight article consists of forty-eight modules and three power collection harnesses, is replaced with four modules fabricated from two mil Kapton H film and ten mil aluminum strips which simulate the mass and approximate thickness of the solar cell stacks and interconnections; the remainder of the panel is simulated using ten mil thick polyvinyl chloride flexible film, re-enforced with four strips of two inch wide fiberglass tape bonded to the PVC. (The model was originally intended to simulate the final design more closely by having the panel assembled from 48 modules, as described above, with simulated harnesses. Due to schedule commitments and lead time for procurement of materials, the PVC panel designs were used as a substitute, even though the resultant adverse effects upon tracking were anticipated.) The two stage, 8,000:1 harmonic drive reduction gearing, designed as a single unit for the flight article by FHC, is replaced using two commercially available harmonic drive reducers mounted in tandem to produce 9600:1 reduction.

Since the purpose of the model was to demonstrate deployment/retraction characteristics of the design, a commercially available 115 volt D.C. electric motor is used as the primary motive power for the mechanical actuation of the design. A conventional laboratory power source is used to provide the required 28VDC for actuation of the launch lock release solenoids and the electric clutch/spring brake unit employed in the drive system. Aluminum tubes are used in lieu of graphite/epoxy composite material for the end bracket sway braces. The power collection harnesses, in the area of the four dummy modules, is simulated using a single sheet of five mil thick Kapton H film; for the remainder of the panel, these harnesses are simulated by the PVC film area. Routing of the power collection harness through the center of the storage drum of the model is omitted as is the slip-ring assembly.

2.5.2 Deployment Test Ground Support Equipment

The model described above is mounted on a rigid steel base to simulate the 20 inch by 100 inch spacecraft mounting surface and is oriented for vertical, upward deployment of the folding arm system and the sub-array panel.

A system of counterbalances (Figure 2.5.2-1) is used to simulate a zero "g" environment. Counterbalance weights are attached through a system of overhead pulleys to each of the three center arms. These counterbalance weights, together with the base and the support at the center of the spreader bar, off-set the weight of the five arm elements of the folding arm system. The weight of the spreader bar and part of the outboard arm element are balanced by a weight attached to the roller chain which is used to counterbalance the weight of the sub-array panel as described below.

Counterbalancing of the sub-array panel presents a problem which is different from the one usually encountered in counterbalancing the weight of a mechanical element. Since the array in the stowed position is wrapped around a drum, its weight is supported by the drum. As the panel is deployed off of the drum, its weight is progressively supported less by the drum and more by the spreader bar. Therefore, the counterbalance system must be configured in a manner which will account for the varying weight of the array panel as it deploys. This is accomplished by using a roller chain having exactly the same weight per linear foot as that of the array panel as measured along its deployment axis. The roller chain is attached to the center of the spreader bar, extends vertically to an overhead chain sprocket wheel system (to support and translate the chain laterally out of the extension plane of the array), and thence extends downward to a point at the same level as

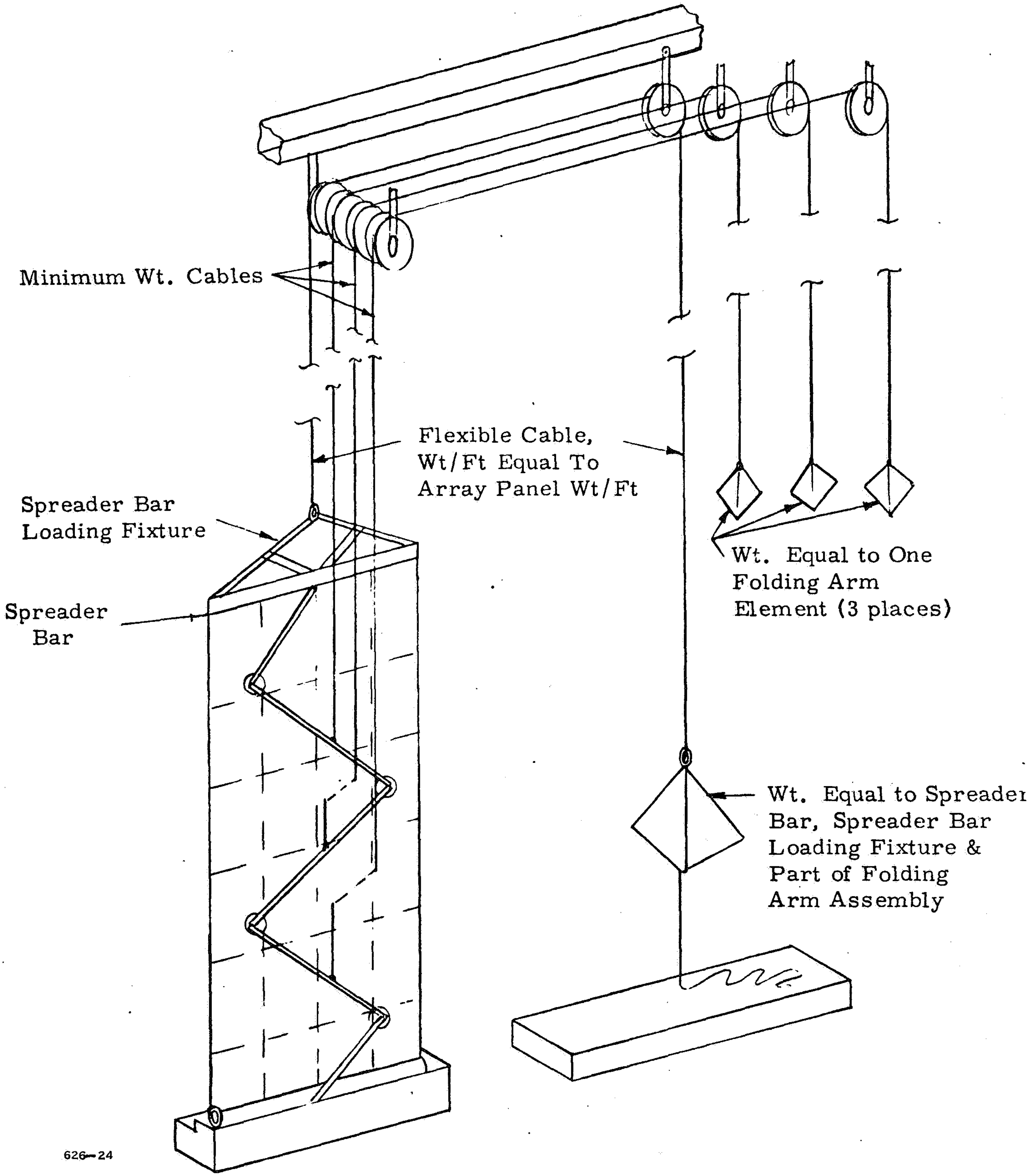


Figure 2.5.2-1 Vertical Deployment Fixture

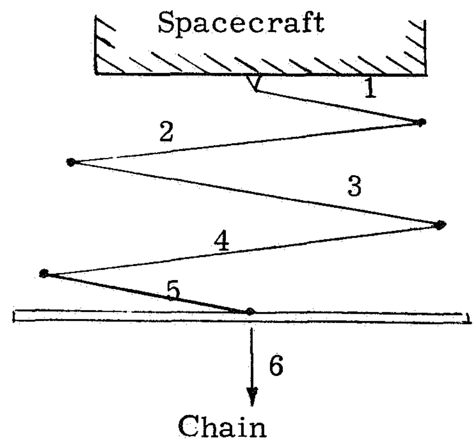
the pivot axis of the storage drum where it terminates and rests upon a support platform. Since the chain and the array have identical weights per linear foot, the weight of the chain between the overhead sprocket system and the support platform exactly counterbalances the weight of that portion of the array which is deployed from the drum plus the weight of the chain remaining between the spreader bar and the overhead sprocket support system.

2.5.3 Model Deployment/Retraction Tests

The deployment ground support equipment described above was fabricated, the model installed and counterbalanced, and deployment/retraction tests were conducted to establish the operational characteristics of the deployment/retraction mechanism. Counterbalance weights and roller chain weights are given below.

TABLE 2.5.3-1

Arm No.	Counterbalance Wt. (lbs)	Cable Rigging Tension(lbs)
1	-	547
2	17.0	426
3	5.5	295
4	16.5	152
5	-	-
(6)	26.0	-
Chain Wt.	0.68 lbs/ft.	



After the array mechanism and panels were counterbalanced, the folding arm mechanism was deployed to the fully extended position and the cable rigging tensions set as shown in Table 2.5.3-1.

The drive system was disengaged at the coupling between the output of the harmonic drive unit and the input shaft of the spiroid gear pinion. The folding arm mechanism was placed in various positions between fully retracted and fully extended (less two or three feet so that the joints were not locked in the fully open position) and the force required to move the spreader bar upward or downward was measured using a calibrated spring scale acting at the center of the spreader bar. In all positions the total force required varied between a minimum of 1 1/2 lbs and a maximum of 2 1/2 lbs. This test graphically demonstrated the very low friction which exists in the system, especially when one considers that the sector gear was driving the pinion gear of the spiroid gear system at the base of the inboard arm element. The forces required to drive the spiroid gear were not determined separately but are considered a significant part of the total measured. The test also indicated that the counterbalance system was indeed in balance. This test was conducted to determine the loads in the system and thereby to insure that the overall system did not impose forces on the folding arm elements and the drive system in excess of that to which they had been designed.

Since the design load had been previously established at ten pounds force acting on the spreader bar, and the deployment forces are on the order of 2.5 pounds maximum, the total system has a margin of safety on the order of 4.

A number of deployment and retraction cycles were performed on the model to determine its mechanical operational characteristics. Significant factors which were uncovered are discussed in the following paragraphs.

<u>Array Panel Tracking on The Storage Drum During Retraction Cycle</u>.

The polyvinyl chloride film panel (described in paragraph above) is flexible, quite elastic, and exhibits very low shear stability properties at room temperatures. Under tension, the film develops wrinkles in the direction of the applied tension which results in a decrease in the width of the panel and a folding over upon itself of the film along the wrinkle lines as the panel is rolled up on the storage drum. The doubling effect results in local increases in the roll diameter of the stored panel and further aggravates, due to the extreme elasticity of the film, the stretching which had been previously noticed. This effect also adversely affected the tracking of the panel upon the storage drum during retraction. The problem does not exist for a panel which is covered with solar cells since the cells impart a lateral stiffening to the substrate and prevent it from wrinkling.

The problem of panel wrinkling was alleviated to a large extent, although not entirely suppressed, by the addition of .025 inch thick by 1/2 inch wide aluminum stiffeners taped to the back face of the PVC film at approximately 1 foot intervals and across its entire width. The stiffeners stabilize the width of the panel and hence reduce the wrinkling tendency. Subsequent tests indicated a marked improvement in the tracking ability of the panel for the first 50% to 70% of the retraction cycle with lateral movement of the panel on the drum limited to no more than 1 inch. However, during the final 30% of retraction, the lack of shear stability in the panel, combined with the build-up of small wrinkles, permitted the panel to advance toward one or the other edge of the storage drum and exceed the permissible tracking error by three or four inches. This condition was further aggravated by inequities in cable tensions.

Cable Rigging Tension Effects

The motion of the joints of the folding arm system is programmed by a cable system which is installed on the four inboard arm elements. Cable tensions are a function of the geometry of the system and of the array panel applied tension. In general, cable tension is highest on the inboard arm element and decreases for each succeeding element, progressing outboard. Cable loads are listed in Table 2.5.3-1 for an array panel applied tension of 10 pounds. It must be recognized that the usable load in each cable system is equal to the difference in tension between the cables located on each side of each arm element. The model was rigged with cable tensions of such magnitude that the active cable would develop only the load required to perform its function without permitting its companion cable to go slack. All cables were pre-stressed to 750 pounds prior to installation of their end terminals in order to pre-stretch the cable and give it a permanent set, thereby preventing subsequent stretching and tension relaxation upon installation in the folding arm system.

The results of the deployment retraction test may be summarized thus:

- The programmed joint motion, folding arm beam mechanism and support structure meets or exceeds the requirements for mechanical operation of extension/retraction of a roll-up solar array. Induced operating loads are substantially below the capability of the design and fall within the predicted range. Thus, substantial margin is available for friction loading contingencies which may be induced by the operational environment.

- The design is relatively sensitive to cable adjustment and tension. Correct tensioning of each of the cables is required to insure satisfactory operation in the areas of: (1) correct sequential lock-up of the joints, (2) relative joint motion (which has a direct bearing upon tracking capability during retraction), and (3) total loading of the drive system.

- The drive system concept of using a differential gear mechanism for dividing the motive power during retraction between the folding arm system and the storage drum has been proven to operate in a satisfactory manner.

- Tracking capability of the array during retraction is highly dependent upon the lateral shear capability of the array panel.

- The counterbalance system employed for the ground test performs its function of simulating a zero "g" environment loading on the mechanism in a satisfactory manner.

2.5.4 Additional Tests Recommended

Potential Solutions To The Array Tracking Problem

The limited number of deployment retraction tests which have been conducted on the folding arm roll-up array system point up a number of the significant factors associated with array tracking. The most significant among them are:

- Folding arm joint motion programming cable tension.

- Adjustment of the full extension position stops at each joint and the relationship of this to the tension which is established in each side of the cable system upon full extension of the total system.
- Amount of total preload in each arm element cabling system relative to the other cable systems.
- Variation in pulley diameters at each end of each cable system.
- Guiding forces imparted to the array by the counterbalancing cables and roller chain system.
- In-plane shear stability and rigidity of the array panel.

Arm elements are designed to withstand the maximum column compression load experienced by the most heavily loaded arm, (Arm No. 1 in Table 2.5.3-1). During the test conducted near the termination of this program, cable tensions in each arm were established to be no greater than that required for the correct functioning of the cable system and hence are equal to the loads shown in Table 2.5.3-1. It is believed that if all cables are tensioned to the maximum capability of the system, the lateral deflection experienced by the folding arm subsystem during deployment/retraction will be minimized. This factor should be established through a suitable test program. It should be noted that correct action of the joint programming system is independent of cable preload tensions as long as the preload in each cable, when under no extension or retraction load, is in excess of 1/2 of the maximum tension developed in the cable at full extension of the system. The maximum cable tension required is 547 pounds. It is recommended that all active cables of the system be preloaded to this value with the system fully extended or 1/2 of this value with the system partially extended and under no extension or retraction forces.

Each joint of the folding arm system, with the exception of the inboard and outboard termination of the folding arm assembly, incorporates a stop to limit the position of the joint in the fully extended mode. These stops are set so that the joint, when fully extended, provides coincident lines of the adjacent arm elements, with the joint under full extension cable tension.

The design uses increased cable tension at each joint during the lock-up process in lieu of a positive mechanical lock. This approach requires a "Boot-Strapping" operation in which the most outboard joint reaches full extension first and is followed sequentially by the remaining joints (as one progresses toward the spacecraft) during the last few degrees of inboard arm element rotation. Once the outboard joint reaches the end of its travel at the stop, the next inboard joint continues to rotate through approximately 1 degree to adequately preload the cables and hold the outboard joint in its fully extended position against in-plane loads that tend to unlock the joint. Of necessity, this system requires some small misalignment of the various joints which increases as one proceeds inboard. The action is compensating to a large degree since adjacent joints fold in the opposite directions. It may be that this system characteristic, combined with inaccuracies in the original preloading of the cables, has contributed to the relatively small lateral motion of the spreader bar during extension and retraction and hence affected the tracking of the array panel during the retraction mode. Further investigation of this phenomenon should be conducted to determine if the effects upon panel tracking of the joint lock-up system is acceptable. Preliminary analyses indicate that the required motion at each joint and, additionally, the required preload for locking the joint may be obtained by the use of pulleys with slightly different diameters at the inboard end of each folding arm element cable system.

It was observed during retraction that the center of the spreader bar followed the extension axis center line quite closely during the first half of the retraction cycle, but that it progressively was displaced laterally to a maximum of six inches reaching the maximum lateral position at approximately 2/3 of retraction and, as a result, contributed to the mistracking of the panel. During the last 1/3 of retraction, the lateral displacement reduced to approximately 2". The lateral motion of the spreader bar may have been reduced somewhat by the support system counterbalance cables. Therefore, in order to prove the system completely, it is recommended that an airbearing table be used for supporting the array panel during horizontal deployment in order that the tracking phenomenon of the panel during roll-up on the storage drum may be accurately assessed.

The shear characteristics of the array panel have a very significant effect upon the tracking characteristics of the panel. Limited element tests using the four dummy modules composed of 2 cm. wide strips of ten mil aluminum bonded to two mil Kapton substrate (which closely simulate the stiffness characteristic to be expected of a module containing solar cell stacks) have shown that the high in-plane shear capability, which is contributed by the cells stacks, has a strong guiding action upon the panel during retraction and, hence, upon its tracking characteristics. This guiding action should be studied in greater depth to determine the effects of initial misalignment of panel attachment to the storage drum and in-plane lateral displacement of the spreader bar/panel combination. The problem does not lend itself to analytical solution and can best be determined empirically through test of the model.

2.6 DESIGN GROWTH CAPABILITIES

Inspection of the Margins of Safety listed in Table 2.4.5-6 indicates that the design exhibits satisfactory safety margins for all components. Moderate increases in loads due to launch or space flight environments can be tolerated with few components requiring redesign. Low positive margins exist in areas which can be easily strengthened by increasing thickness at modest weight penalties.

Spacecraft maneuvering loads defined in the Specification (Ref. 1) are not a critical design load for any component. Therefore, such loads may be increased substantially without requiring redesign.

The array design was investigated for its capability to withstand thermal shock and extreme temperatures that would be encountered in a 100 n.m. Earth orbit. It was found to be capable of withstanding this severe environment without redesign although array panel temperatures will reach a maximum of 217° F near the folding arm elements and 181° F at distances over nine inches from the arm elements.

At Venus mean distance, the array will attain a maximum temperature near the arm of 270° F and a temperature of 211° F at points over nine inches from the arm.

An acceptably small gradient exists across the folding arm element in both cases; 7° F near Earth and 16° F at the Venus mean distance.

Power output of the array at Mars mean distance is reduced but, due to lower operating temperature, the voltage will increase from 78 VDC to 96 VDC, an acceptable value for state-of-the-art power conditioning equipment.

The power/weight ratio may be improved by decreasing system structural weight. One area which lends itself to weight savings are the end brackets, presently designed as a standard sheet metal and stringer beam fabricated from aluminum alloy. Graphite/Epoxy composite material may prove to be acceptable with redesign of this structure. An estimated weight saving of one to two pounds appears feasible. However, because of the complex loadings in the end brackets, the ability of the graphite/epoxy material to withstand the loads satisfactorily can be determined only be test.

Higher reliability of the mechanical components can be realized by incorporating redundant bearings (bearings within bearings). This approach will increase the weight of the design substantially, not only by the addition of more bearings but also the increased fitting material needed to enclose the larger outside bearing diameters. The decision as to the necessity for this approach with the attendent weight penalties is considered outside the scope of this study.

3.0 CONCLUSIONS

The objective of the study program is to determine the feasibility of fabricating a 250 $ft.^2$ roll-up solar array capable of producing 30 watts/lb. or more under the conditions specified in Reference 1. This objective has been met. A preliminary design has been accomplished which produces 34.5 watts/lb. A full scale, mechanically functioning model of the design has been fabricated and has successfully demonstrated the ability of the selected design to deploy and retract.

4.0 RECOMMENDATIONS

With the successful conclusion of Phase I of the program, the next logical effort should be to design, fabricate and conduct qualification tests on a flight quality solar array. It is recommended that the array be full size so that scale modeling effects (which are often difficult to assess) are not a factor in the final evaluation.

The most important recognized question which must be attacked is that of satisfactory tracking of the array panel onto the storage drum during retraction cycling. This problem can best be investigated and evaluated using an array panel fabricated to flight hardware specifications.

5.0 NEW TECHNOLOGY

No reportable items of New Technology have been uncovered during this study program.

6.0 REFERENCES

1. JPL Document No. 501407A, "Roll-Up Solar Cell Array, 30 Watts/Lb., Detail Requirements for", dated 1/4/67.

2. Fabrication Feasibility Study of a 30 Watt/Lb. Roll-Up Solar Array, First Quarterly Report, FHC Doc. No. 652-00101-QR, dated 10/15/68.

3. Fabrication Feasibility Study of a 30 Watt/Lb. Roll-Up Solar Array, Second Quarterly Report, Fairchild Hiller Document No. 652-00102-QR, dated 2/2/68.

4. Fabrication Feasibility Study of a 30 Watt/Lb Roll-Up Solar Array, Third Quarterly Report, Fairchild Hiller Document No. 652-00103-QR, dated 4/15/68.

5. Stress Analysis, Final Report - Fabrication Feasibility Study of a 30 Watt/Pound Roll-Up Solar Array. Fairchild Hiller Document No. 652-SA-3001.